NEW

HOW IT WORKS

BOOK OF

VOLCANOES & EARTHQUAKES











INSIDE AN ERUPTION • DEADLY LAVA • LANDSLIDES • PYROCLASTIC FLOWS • GEYSERS • TSUNAMIS



WELCOME TO

HOW IT WORKS BOOK OF VOLCANOES & EARTHQUAKES

For all man's achievements over the past centuries, every now and then we're reminded that ultimately, we're all at the mercy of nature. In seconds, something that has remained dormant for decades can suddenly awaken, destroying a city and demolishing everything in its path. A calm day can quickly turn to catastrophe as the ground shakes and buildings crumble. In this book, we take a detailed look at two of nature's most powerful forces; volcanoes and earthquakes. Explaining how and why they occur, you'll discover how they affect our lives, and how they shape our landscape. Packed with illustrations and incredible images of the damage they can do, you'll also find case studies from Etna and Vesuvius to Christchurch and Haiti. So read on to learn more about the deadly power of the natural world.

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CONTENTS



p.70
HAWAIIAN-STYLE ERUPTIONS

VOLCANOES

What is a volcano?	10	Shield volcanoes	40	Volcanic complexes	66
The world's volcanoes	12	Cinder cones	42	Fissure eruptions	68
Volcanic eruptions	14	Stratovolcanoes	46	Hawaiian-style eruptions	70
Eruption types	16	Etna	48	Strombolian eruptions	74
Volcano types	20	Merapi eruption 2010	50	Vulcanian eruptions	76
Lava	22	Calderas	52	Peléan eruptions	78
Aerial products	26	Supervolcanoes	54	Plinian eruptions	80
Pyroclastic flows and surges	28	Maars	56	Vesuvius	82
Volcanic mudflows	32	Exploding lakes	58	Novarupta 1912	84
Continental volcanic arcs	34	Tuff rings and cones	60	Mount St Helens	86
Volcanic island arcs	36	Lava domes and spines	62	Phreatic eruptions	90
Volcanic island chains	38	Volcanic fields	64	Subglacial volcanoes	92



p.86
MOUNT ST HELENS



p.20
VOLCANO TYPES

Eyjafjallajökull	94
Antarctic volcanoes	98
African Rift volcanoes	100
Nyiragongo disaster	102
Volcanic remnants	104
Monitoring volcanoes	106
Living with volcanoes	108
Volcanic hot springs	110
Fumaroles	112
Geysers	114
Mud volcanoes	116
The Lusi disaster	118



p.132
MEASURING EARTHQUAKES

EARTHQUAKES

What is an earthquake?	122	Sichuan, China 2008	
Earthquake zones	124	Strike-slip earthquakes	144
Causes of earthquakes	126	Izmit 1999	
Haiti 2010	128	Christchurch 2011	148
Movements and faults	130	Seismic destruction	152
Measuring earthquakes	132	Bam 2003	154
Subduction earthquakes	136	Quake-triggered landslides	156
Concepción 2010	138	Living with earthquakes	158

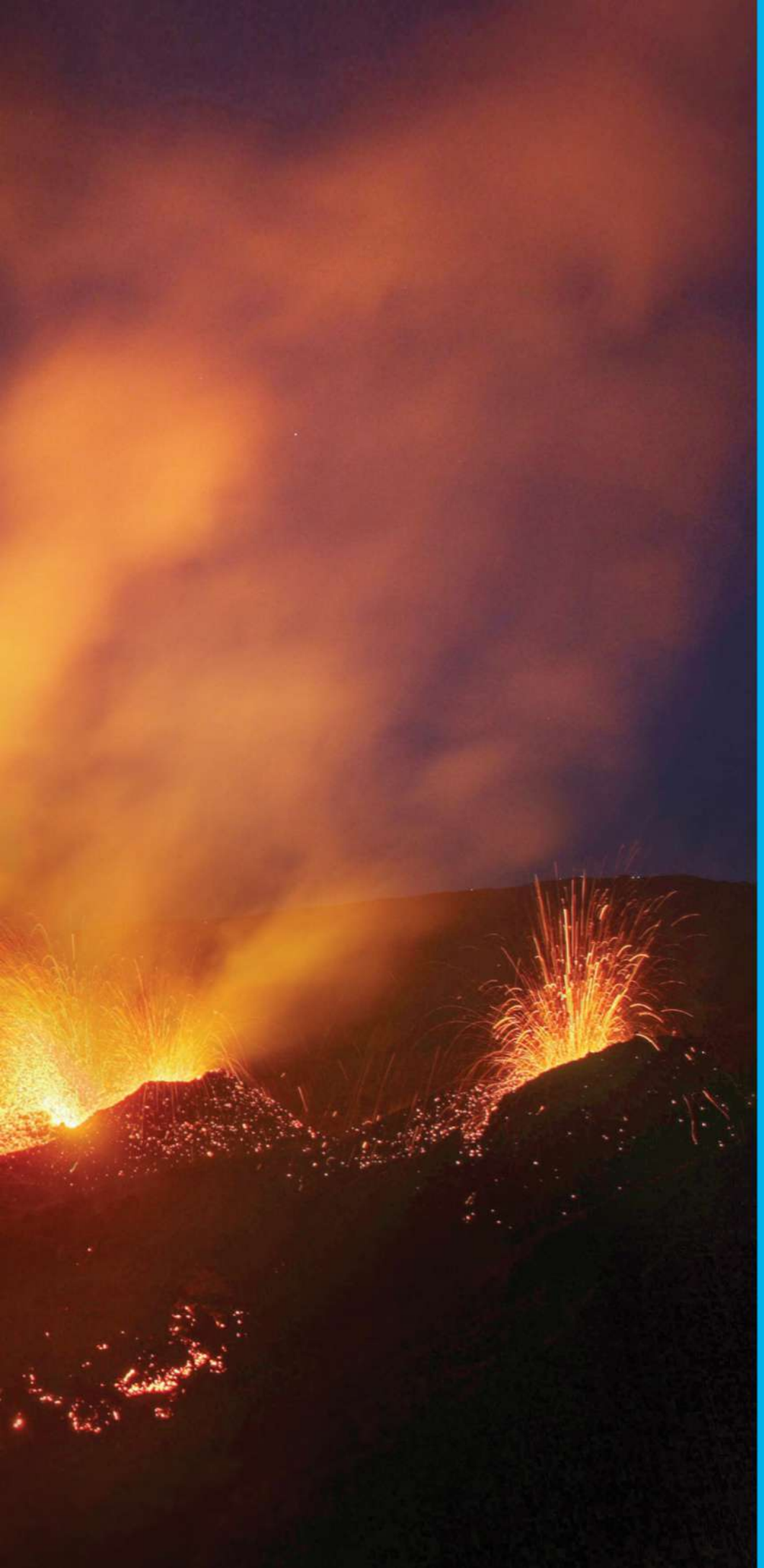


p.140
SICHUAN, CHINA



p.122
WHAT IS AN EARTHQUAKE?





VOLCANOES

<< Eruption
This dramatic eruption occurred on the flank of Piton de la Fournaise, a shield volcano on Réunion Island in the Indian Ocean.

WHAT IS A VOLCANO?

A volcano is an opening in Earth's crust where magma – a mixture of red-hot molten rock, mineral crystals, rock fragments, and dissolved gases – from inside the planet erupts onto the surface. Magmatic volcanoes like this are by far the best known type, but there is a second, less well known type that erupts mud rather than magma (see pp.116–17).

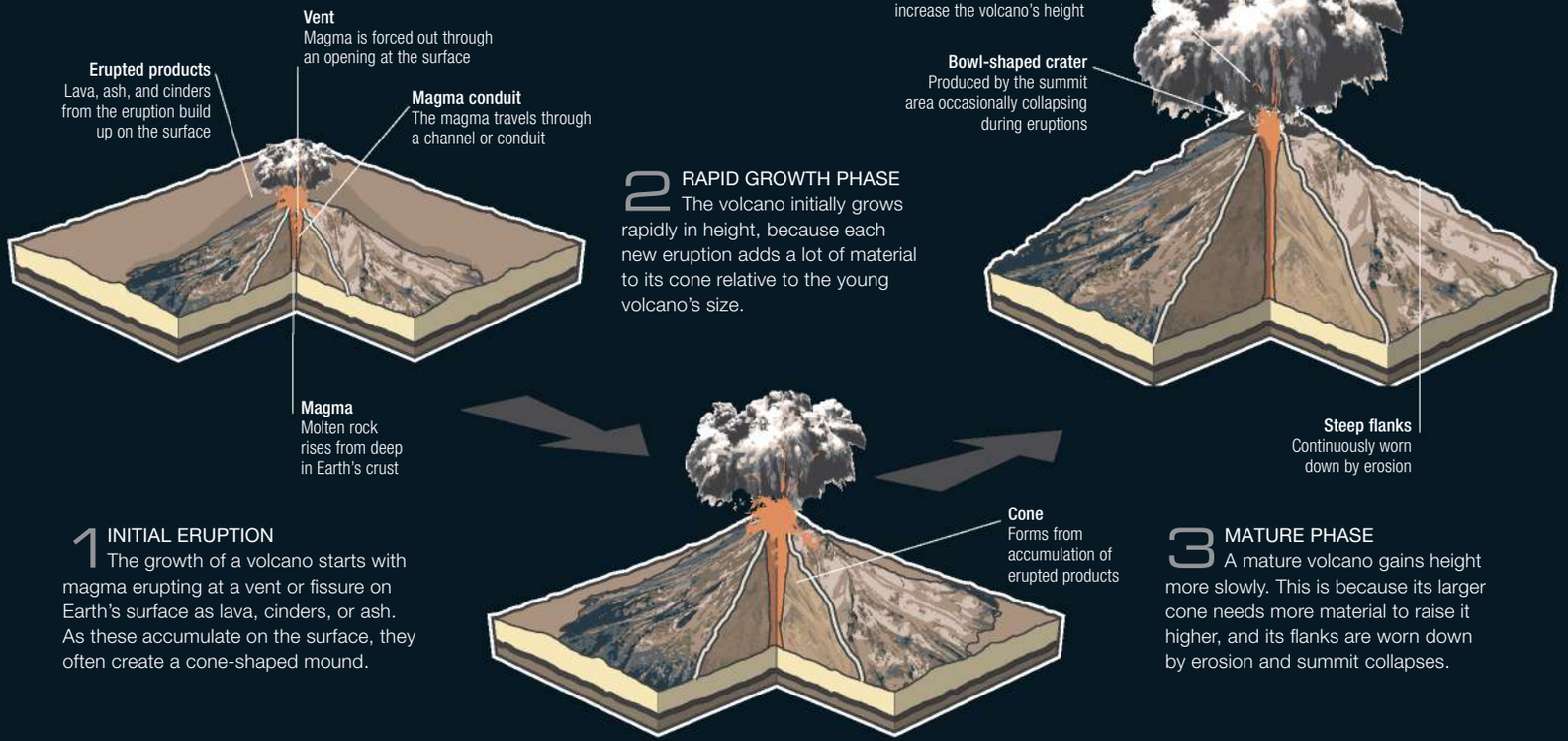
CREATION OF A VOLCANO

Magma is produced by the melting of rock in the Earth's upper mantle and lower crust. This occurs only at certain places, notably at convergent and divergent plate boundaries and at hotspots or mantle plumes. Magma is usually less dense than the surrounding rock because it is hotter (heating matter causes it to expand), so it rises up, travelling through weaknesses or fractures in the crust all the while incorporating small to large amounts of the surrounding bedrock called lithic fragments. Eventually it collects in large cavities called magma chambers, several kilometres below Earth's surface. From there, the magma rises through channels called conduits or pipes until it reaches the surface or, in the case of a submarine volcano, the ocean floor. There, the magma escapes either through an opening, called a vent, or a crack, called a fissure. The escape of the magma is known as an eruption, and it can vary from a quiet outpouring – in the form of a fountain or stream of lava – to a highly explosive event in which the magma and contained gases are blown violently into the air and can travel down the slopes of the volcano at great speeds in the form of a pyroclastic flow, a mixture of hot rock, gas, and ash.

GROWTH OF A VOLCANO

Volcanoes grow mainly from the accumulation of their own eruptive products – solidified lava, cinders, and ash. Lava is the name given to magma when it flows out of a volcano. This molten material eventually cools and solidifies to form solid rock. Cinders and ash are magma that has been blown into the air, cooled, then deposited as solid fragments. Different types of volcano build up either by the accumulation of one main material, such as cinders of lava flows, or from a combination of several products. Volcanoes can also grow partly by intrusion – when magma moves up within the volcano and solidifies internally, pushing overlying rock upwards to form a bulge. As they grow, many volcanoes develop a classic volcano shape, a steep-sided cone. However, not all volcanoes are cones: some are broad, gently sloping shield-shaped structures, while others consist of enormous shallow craters or water-filled depressions in the ground. Volcanoes vary considerably in their activity, so their growth is very intermittent. Some can continue growing for millions of years before the supply of magma runs out and they become extinct.

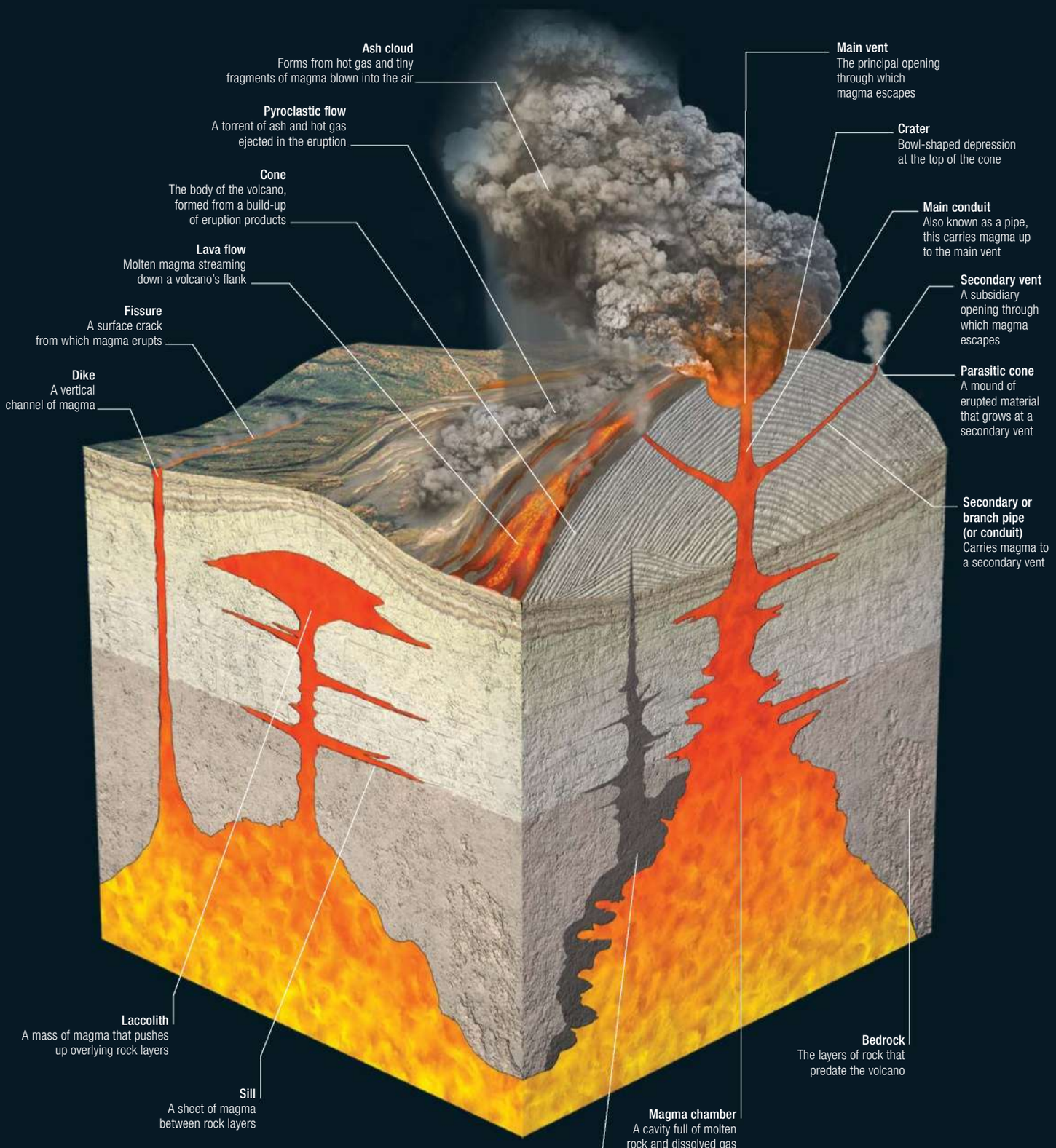
THE SEQUENCE OF GROWTH



1 INITIAL ERUPTION
The growth of a volcano starts with magma erupting at a vent or fissure on Earth's surface as lava, cinders, or ash. As these accumulate on the surface, they often create a cone-shaped mound.

2 RAPID GROWTH PHASE
The volcano initially grows rapidly in height, because each new eruption adds a lot of material to its cone relative to the young volcano's size.

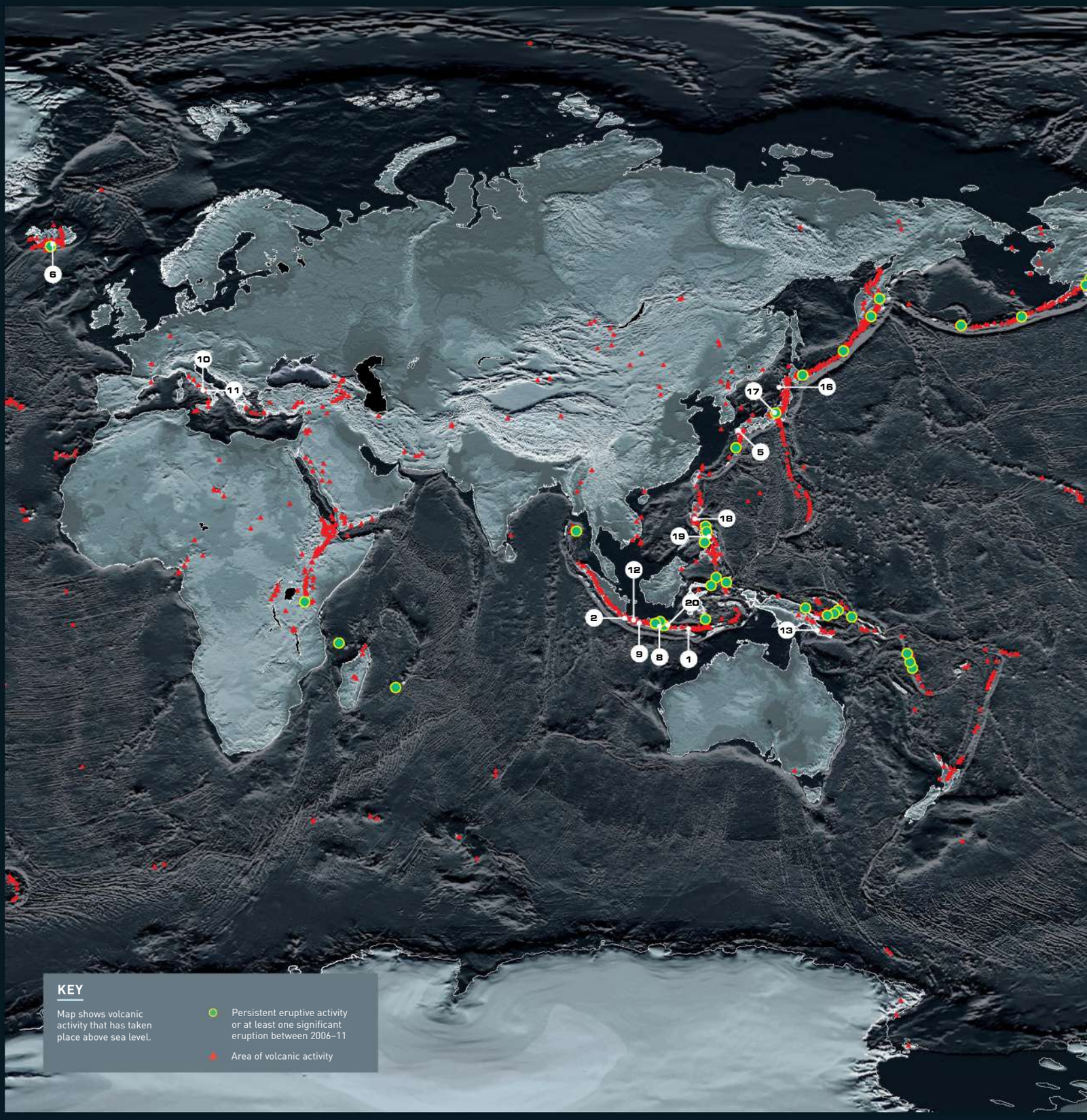
3 MATURE PHASE
A mature volcano gains height more slowly. This is because its larger cone needs more material to raise it higher, and its flanks are worn down by erosion and summit collapses.



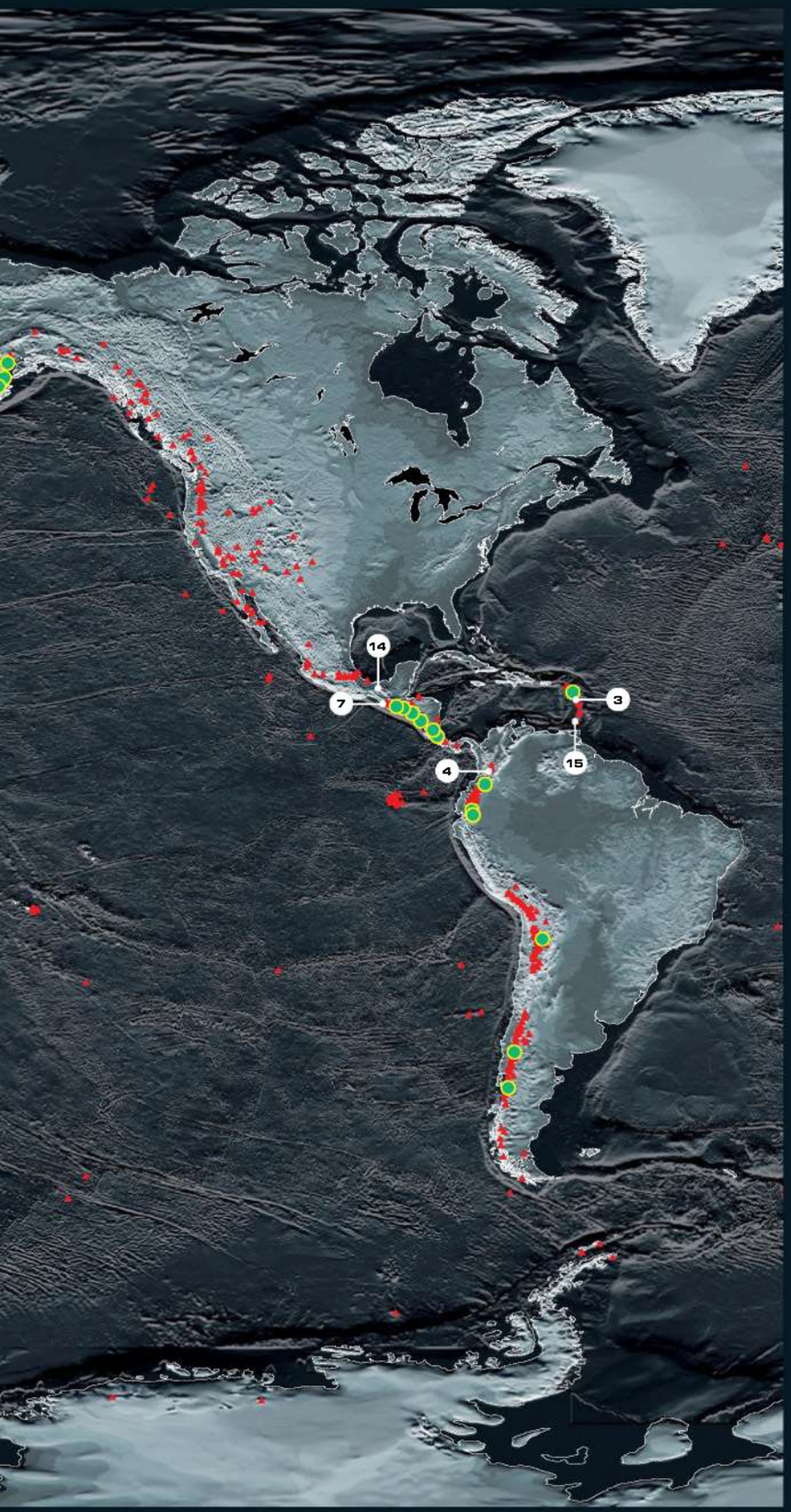
INSIDE A STRATOVOLCANO

The source of a volcano's activity is a magma chamber – a cavity containing molten rock and gas that lies 1–10km (0.6–6 miles) below Earth's surface. A volcano usually has one main conduit or pipe through which magma from this chamber reaches the surface, but it can also erupt from secondary or side vents, forming parasitic cones, or from surface fissures. Magma may also intrude into the surrounding rock without reaching the surface, forming subterranean structures such as dikes, sills, and laccoliths, which eventually cool to form solid bodies.

THE WORLD'S VOLCANOES



Volcanoes are heavily concentrated in a few areas of the world, mainly close to plate boundaries, particularly the "Ring of Fire" around the edges of the Pacific Ocean. Other concentrations are in Iceland, eastern Africa, the eastern Caribbean, at the "hotspots" of Hawaii in the central Pacific, and the Galápagos Islands in the eastern Pacific.



MOST LETHAL VOLCANIC ERUPTIONS IN HISTORY

1 MOUNT TAMBORA
Country Indonesia
Date 1815
Deaths 92,000

2 KRAKATAU
Country Indonesia
Date 1883
Deaths 36,417

3 MONT PELÉE
Country Martinique
Date 1902
Deaths 29,025

4 NEVADO DEL RUIZ
Country Colombia
Date 1985
Deaths 25,000

5 MOUNT UNZEN
Country Japan
Date 1792
Deaths 14,300

6 LAKI
Country Iceland
Date 1783
Deaths 9,350

7 SANTA MARÍA
Country Guatemala
Date 1902
Deaths 6,000

8 KELUT
Country Indonesia
Date 1919
Deaths 5,110

9 GALUNGGUNG
Country Indonesia
Date 1882
Deaths 4,011

10 MOUNT VESUVIUS
Country Italy
Date 1631
Deaths 3,500

11 MOUNT VESUVIUS
Country Italy
Date 79CE
Deaths 3,360

12 PAPANDAYAN
Country Indonesia
Date 1772
Deaths 2,957

13 MOUNT LAMINGTON
Country Papua New Guinea
Date 1951
Deaths 2,942

14 EL CHICHÓN
Country Mexico
Date 1982
Deaths 2,000

15 SOUFRIÈRE
Country St Vincent
Date 1902
Deaths 1,680

16 OSHIMA-OSHIMA
Country Japan
Date 1741
Deaths 1,475

17 ASAMA
Country Japan
Date 1783
Deaths 1,377

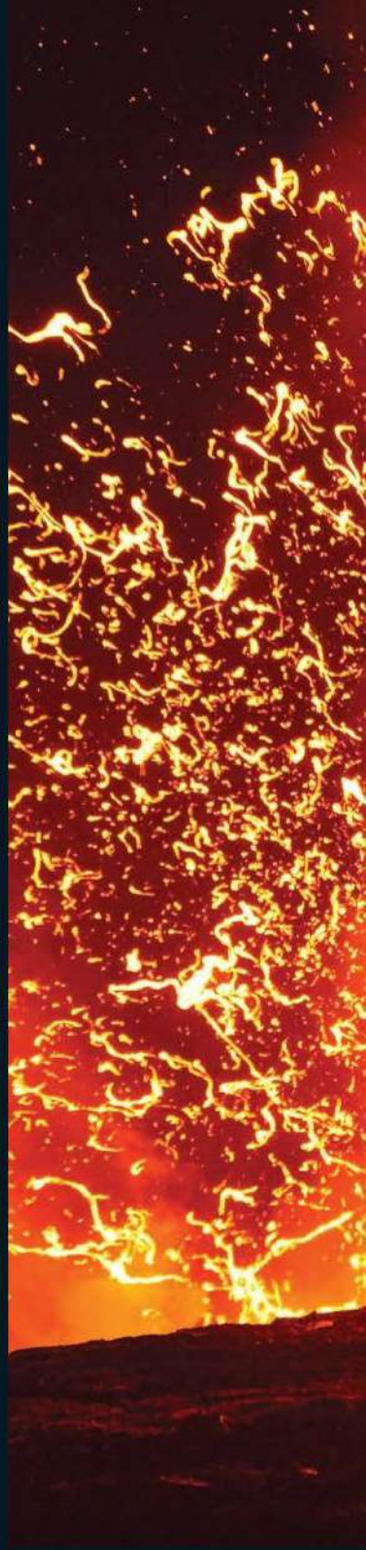
18 TAAL
Country Philippines
Date 1911
Deaths 1,335

19 MAYON
Country Philippines
Date 1814
Deaths 1,200

20 AGUNG
Country Indonesia
Date 1963
Deaths 1,184

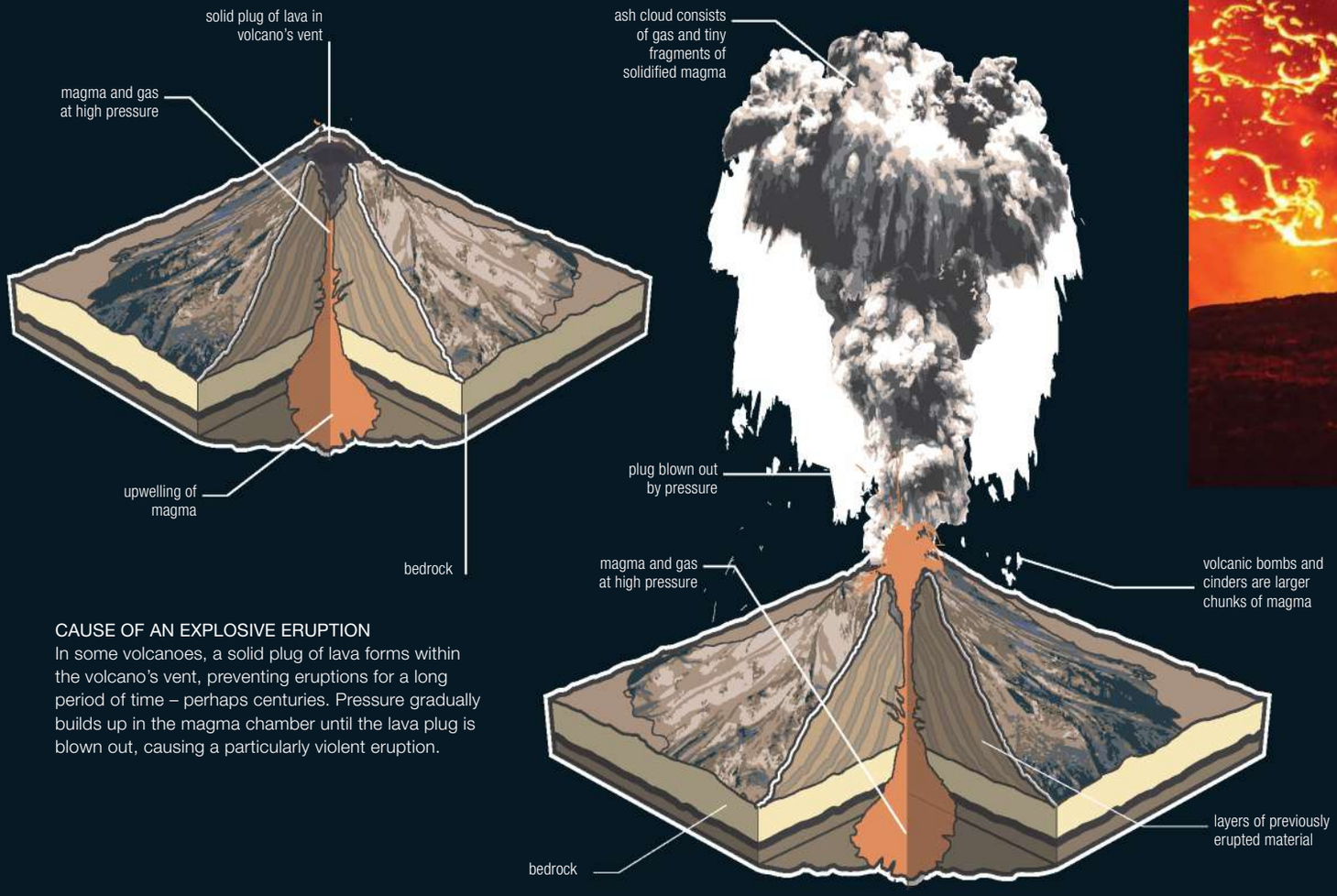
VOLCANIC ERUPTIONS

Volcanoes are of interest and potentially dangerous because of their eruptions. These fall into two broad categories, called effusive and explosive. In effusive eruptions there is a relatively quiet outpouring of lava. Explosive eruptions are characterized by explosions in which hot gas and magma are propelled into the air.

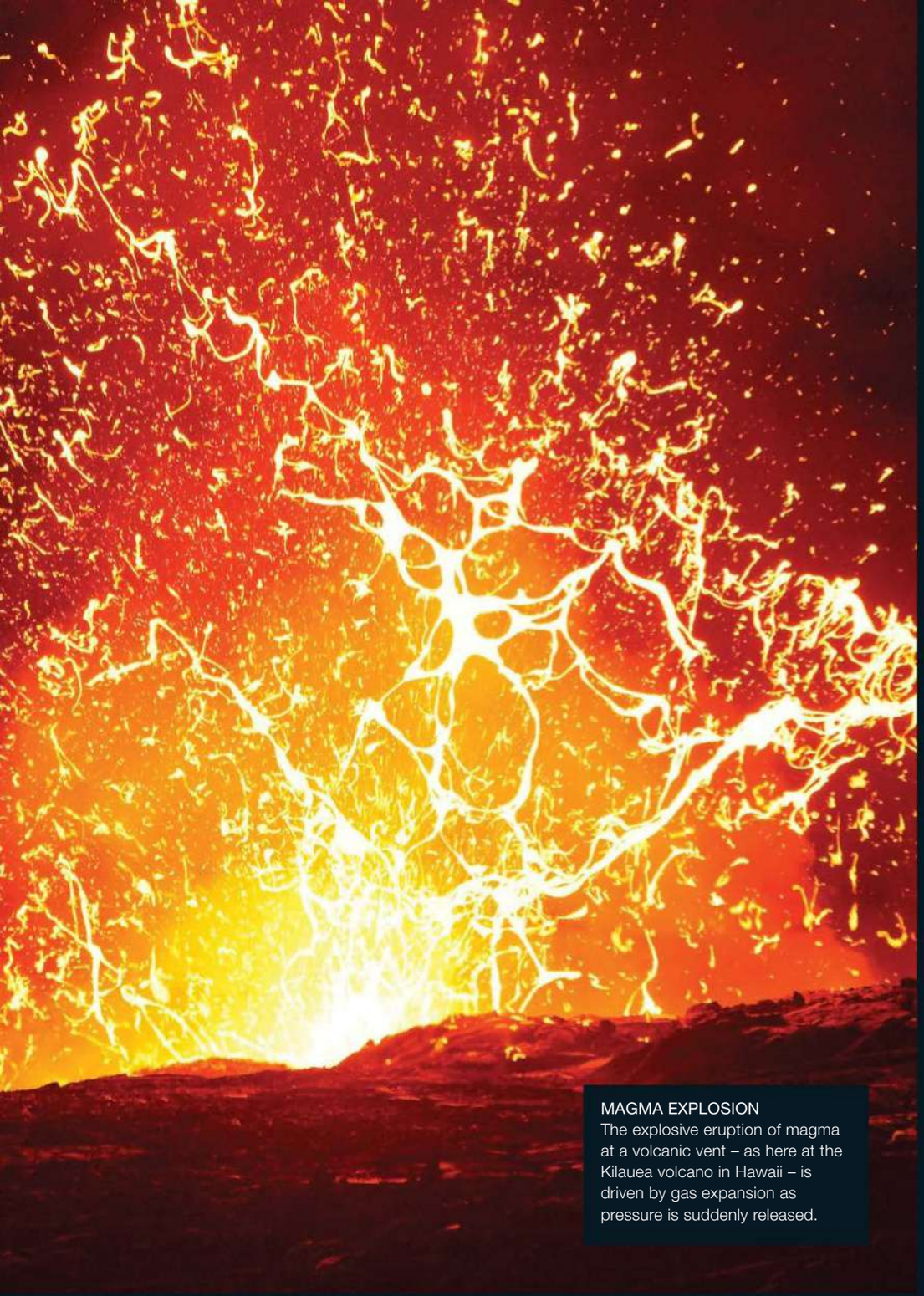


CAUSES AND TRIGGERS

Many factors affect when a volcano will erupt and what sort of an eruption it will be. These include the amount of magma (melted rock) in the volcano, its composition and viscosity (thickness), the amount of dissolved gases it contains, and the pressure in the magma chamber. In many cases, the trigger for an eruption is the upwelling of new magma. As the magma rises, the pressure inside it decreases and the dissolved gases form bubbles, which expand quickly, causing a further surge upwards. If the magma contains little gas it may simply flow onto the surface, particularly if it is a non-viscous (runny) type. But in many volcanoes, the magma both contains a large amount of gas and is highly viscous, meaning that it can hold in this gas until the external pressure has fallen to almost nothing. As magma of this type approaches the surface, and the overlying pressure drops rapidly, the trapped gas suddenly escapes all at once. The result is a highly explosive eruption as pressure is released, and gases dissolved in the trapped magma turn into a mass of expanding bubbles. This causes the magma to fragment into ash particles and be expelled upwards. If rising magma comes in contact with surface or groundwater, the result can be a violent explosion of steam together with ash formed from the sudden breakup of the magma. This is called a phreatomagmatic eruption.



CAUSE OF AN EXPLOSIVE ERUPTION
In some volcanoes, a solid plug of lava forms within the volcano's vent, preventing eruptions for a long period of time – perhaps centuries. Pressure gradually builds up in the magma chamber until the lava plug is blown out, causing a particularly violent eruption.



MAGMA EXPLOSION
The explosive eruption of magma at a volcanic vent – as here at the Kilauea volcano in Hawaii – is driven by gas expansion as pressure is suddenly released.

> "THE REASON OF THESE FIRES IS THE ABUNDANCE OF SULPHUR AND BRIMSTONE...IN THE BOSOME OF THE HILL."
>
> **SIR THOMAS POPE BLOUNT,** IN A NATURAL HISTORY: CONTAINING MANY NOT COMMON OBSERVATIONS (1693).

VOLCANIC ACTIVITY

Volcanoes were once categorized as either active, dormant, or extinct, according to the frequency of their eruptions, but volcanologists no longer use this classification. Some volcanoes are still categorized as extinct if they clearly no longer have a magma supply. All other volcanoes are considered active, though a distinction is made between volcanoes that have erupted at least once in recorded history (called historically active), and those for which there is evidence only of an eruption in the past 10,000 years (Holocene active). There are about 1,550 holocene active volcanoes in the world of which 573 have historical eruptions.

ERUPTION MAGNITUDE

The strength of volcanic eruptions is measured on the Volcanic Explosivity Index or VEI scale (see below). The VEI value is based on the height of an eruption's ash plume or column and an estimate of the volume of material that is expelled. Particular eruption types (see pp.16–17) often have similar VEIs. For example, Strombolian eruptions usually have a VEI value of 1 or 2, while Plinian eruptions have a VEI of 5 or 6.

MEASURING VOLCANIC ERUPTIONS
The Volcanic Explosivity Index is the volcano equivalent of the Richter Scale. Eruptions with small VEI numbers are common, those with high numbers are rare. Thus, only five eruptions with a VEI of 6 or 7 have occurred since 1800, and eruptions with a VEI of 8 occur only about once in 100,000 years.

VOLCANIC EXPLOSIVITY INDEX (VEI)

VEI	DESCRIPTION	HEIGHT OF COLUMN	VOLUME OF MATERIAL	EXAMPLE	YEAR
0	**Non-explosive**	Up to 100m (330ft)	Up to 10,000m^3 (350,000ft^3)	**Mauna Loa**	Various
1	**Gentle**	100–1,000m (330–3,300ft)	Over 10,000m^3 (350,000ft^3)	**Stromboli**	Various
2	**Explosive**	1–5km (½–3 miles)	Over 1 million m^3 (35 million ft^3)	**Tristan da Cunha**	1961
3	**Severe**	3–15km (2–9 miles)	Over 10 million m^3 (350 million ft^3)	**Etna**	2003
4	**Cataclysmic**	10–25km (6–15 miles)	Over 0.1km^3 (0.02 miles^3)	**Eyjafjallajökull**	2010
5	**Paroxysmal**	Over 25km (15 miles)	Over 1km^3 (0.2 miles^3)	**Mount St Helens**	1980
6	**Colossal**	Over 25km (15 miles)	Over 10km^3 (2 miles^3)	**Krakatau**	1883
7	**Super–colossal**	Over 25km (15 miles)	Over 100km^3 (25 miles^3)	**Tambora**	1815
8	**Mega–colossal**	Over 25km (15 miles)	Over 1,000 km^3 (240 miles^3)	**Toba**	70,000 years ago

ERUPTION TYPES

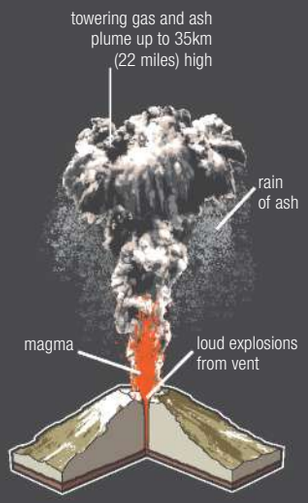
Volcanic eruptions are usually thought of as sudden, cataclysmic explosions that produce large quantities of lava, ash, and other volcanic products. In practice, volcanoes can erupt in any of several different ways. A single volcano can erupt in different styles during separate eruptions or even during separate stages in the same eruption.



1991 ERUPTION OF PINATUBO
An eruption of Mount Pinatubo in the Philippines in June 1991 (above) was one of just a handful of Plinian eruptions in the 20th century. It produced a 34-km (21-mile) high ash column and killed more than 800 people.

PLINIAN

These extremely violent eruptions produce colossal plumes of gas and ash. Rare, extra-large ones are termed ultraplinian. See also Plinian Eruptions, pp.80-81.

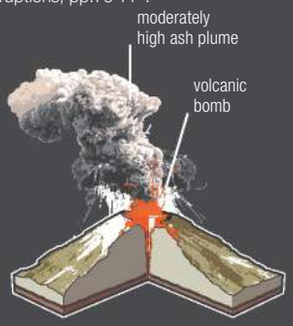




PICHINCHA PHREATIC ERUPTION
A large mushroom cloud of steam and ash rises from Guagua Pichincha, Ecuador, in 1999.

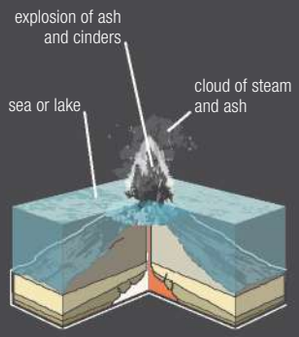
VULCANIAN

Eruptions of this type usually start with a noisy explosion and feature volcanic bombs and an ash plume, often followed by a lava flow. See also Vulcanian Eruptions, pp.76-77-.



SURTSEYAN

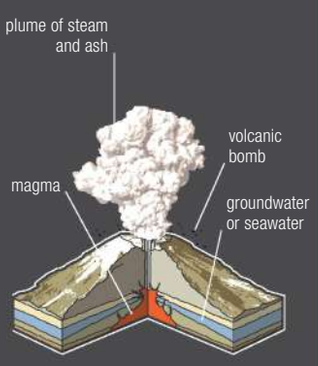
Surtseyan eruptions result from the top of an underwater volcano reaching the surface and subsequently producing vigorous explosions.



KILAUEA LAVA FOUNTAIN
Hawaiian-style eruptions are so-named because the large Hawaiian volcanoes Mauna Loa and Kilauea (right) usually erupt in this manner.

PHREATIC

Caused by volcanically heated rock coming in contact with cold groundwater or surface water, phreatic eruptions feature explosions of steam, ash, volcanic bombs, and rock. Related eruptions caused by interactions between magma and water are termed phreatomagmatic. In either case, no incandescent lava is produced, and there are no lava flows. See also Phreatic Eruptions, pp.90-91.

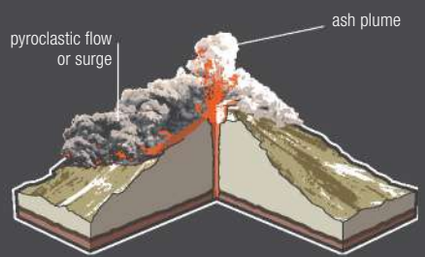


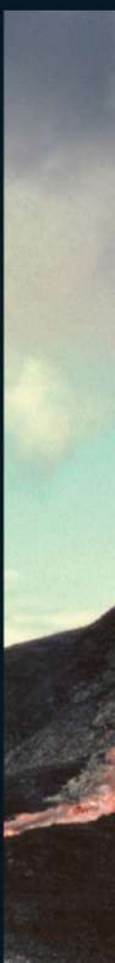


ASH AND GAS FLOW, MONTSERRAT
A pyroclastic flow – hot gas mixed with ash and rock fragments – flows down a slope on the Soufrière Hills volcano on the Caribbean island of Montserrat. Events like this are a hallmark of Peléan-type eruptions.

PELÉAN

An important characteristic of this eruption type is a flow of pyroclastic material (mixture of hot gas and ash) at speeds up to 160kph (100mph) down the volcano's flank. See also Peléan Eruptions, pp.78-79.







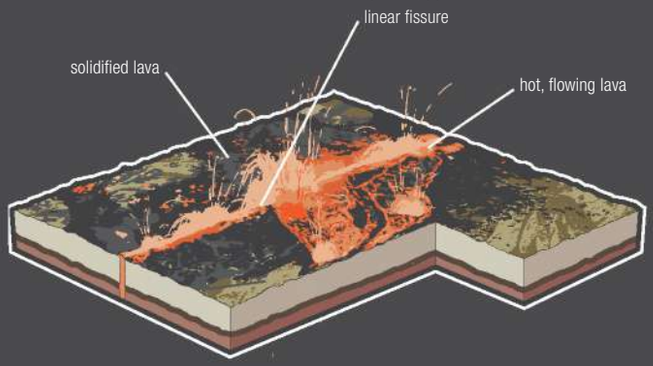
FISSURE AT KRAFLA
Fissure eruptions are also known as Icelandic-style eruptions, since they occur commonly in Iceland, as in the eruption of the Krafla volcano (left).

STROMBOLI AT NIGHT
Strombolian eruptions are named after the small stratovolcano Stromboli (below), off the coast of Sicily, which almost continuously produces eruptions of this type.



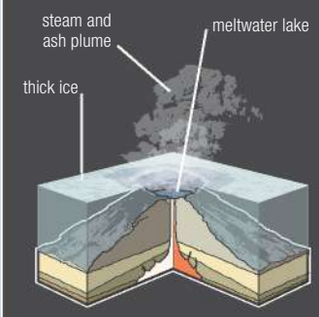
FISSURE OR ICELANDIC

The main characteristic of this eruption type is the appearance of a long straight fissure in the ground. Large amounts of runny lava pour quietly out of the fissure, sometimes via a line of small lava fountains. See also Fissure Eruptions, pp.68-69.



SUBGLACIAL

Where a volcano erupts under an ice cap or other type of glacier, it is called a subglacial eruption. See also Subglacial Volcanoes, pp.92-93.



STROMBOLIAN

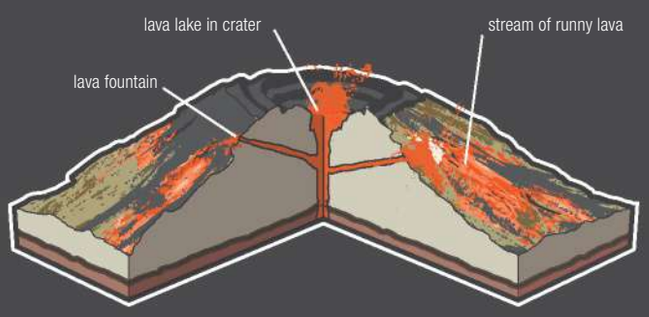
Eruptions of this type emit fountains and little bombs of lava at rhythmic intervals, sometimes interspersed with lava flows. See also Strombolian Eruptions, pp.74-75.





HAWAIIAN

In a Hawaiian-style eruption, there are relatively quiet outpourings of lava in the form of streams and fountains, usually from fissures on the volcano's flanks. Sometimes lava spills out of a lava lake in the summit crater. See also Hawaiian-Style Eruptions, pp.70-71.







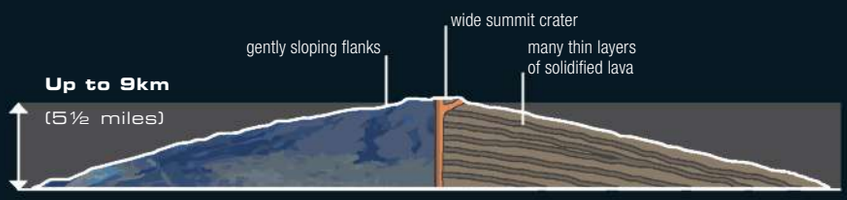
BURIED IN LAVA
The rusted top of a school bus protrudes from a field of solidified pahoehoe lava erupted from the Hawaiian shield volcano Kilauea in 1990. The lava flow, which also buried most of two small towns, Kalapana and Kaimu, was just one phase in an eruption that continued for more than 30 years.

VOLCANO TYPES

As well as erupting in a variety of ways, volcanoes take many different forms. The most familiar type is a large, steep-sided cone, but there are many other varieties, from much smaller cones to extensive gently sloping areas of lava and water-filled depressions in the landscape. The form of volcano likely to be found in any part of the world depends on factors such as the type of magma (molten rock) formed within Earth's crust in that region.

SHIELD VOLCANOES

The giants of the volcano world are known as shield volcanoes. Shaped like broad, upturned shields, they are made of layer after layer of runny lava that flowed over the surface and then solidified. Shield volcanoes are typically formed above hotspots. See also pp. 40–41.



PITON DE LA FOURNAISE
Here, a small secondary cone is visible on the flank of the massive Piton de La Fournaise shield volcano, which forms part of the Indian Ocean island of Réunion.

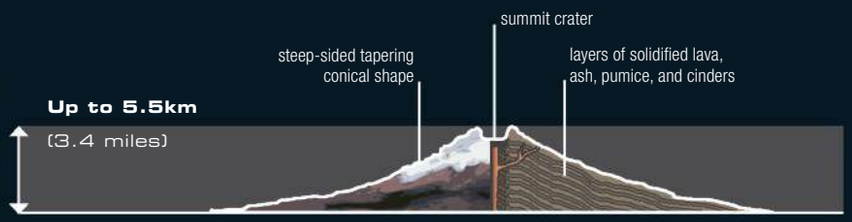




REDOUBT VOLCANO
Situated on the coast of Alaska, Mount Redoubt is a large stratovolcano that erupted spectacularly in 1989–90 and again in 2009, producing enormous ash clouds.

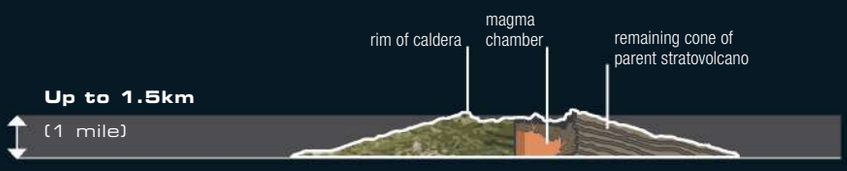
STRATOVOLCANOES

Tall, steep-sided volcanoes, composed of successive layers of different types of volcanic product, are called stratovolcanoes, or composite volcanoes. A common type of volcano, they form in parts of the world where viscous magma reaches Earth's surface. When they erupt, they often do so extremely violently. Many of the world's most famous volcanoes, such as Mount St Helens and Etna, are of this type. See also pp. 46–49.



CALDERAS

If the upper part of a stratovolcano collapses following a cataclysmic eruption, the result is a caldera. This consists of a wide, deep crater, beneath which (in a still active volcano) lies a magma chamber. Many calderas are filled with water or even partly submerged. Some contain new volcanic cones or other volcanic features growing within them. See also pp. 52–53.



QUILOTOA CALDERA
This caldera in the Ecuadorian Andes formed about 800 years ago following the partial collapse of a stratovolcano. It now contains a deep lake, coloured green by dissolved minerals.

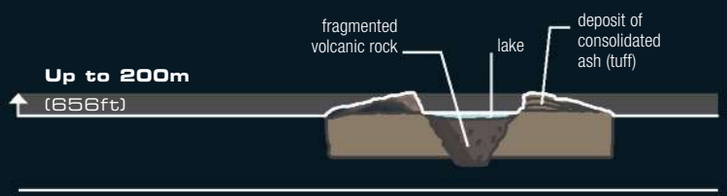




ZUNI SALT LAKE
Located in New Mexico, Zuni Salt Lake occupies the lower part of a maar that is about 2,000m (6,500ft) across and 120m (390ft) deep. A sacred Native American site, the lake frequently dries out to leave salt flats. At its edge are two small cinder cone volcanoes.

MAARS

Volcanoes known as maars consist of relatively small, shallow, bowl-shaped craters sunk slightly into the ground. They are often filled with water to produce lakes, though there are also some dry maars in desert areas. They form as a result of explosions when magma comes into contact with groundwater or permafrost as it rises towards the surface. See also pp. 56–57.





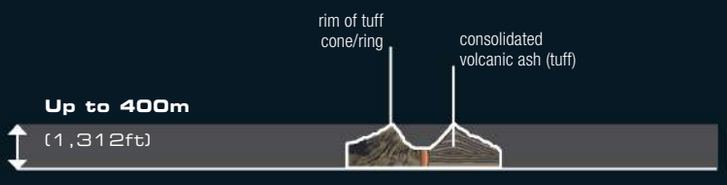
HAWAIIAN CONE
This tuff cone on O'ahu, Hawaii, is called Koko Crater. Like most tuff rings and cones, it formed in a single eruptive phase and is not expected to be active again.



TWIN CONES
These two cinder cones form part of a volcanic landscape called the Mountains of Fire on Lanzarote, one of the Canary Islands.

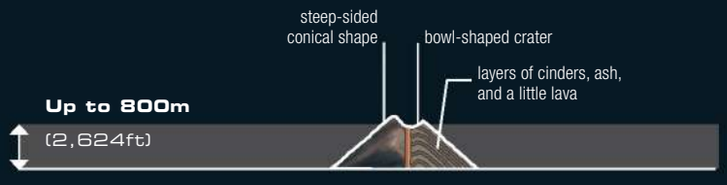
TUFF CONES AND RINGS

These are small volcanoes with bowl-like central craters. They are formed in a similar way to maars – by rising magma coming in contact with groundwater or the sea. The resulting reaction produces a lot of volcanic ash, which accumulates in a cone or ring and consolidates to form a rock called tuff. See also pp. 60–61.



CINDER CONES

The relatively small cinder cones are composed mainly of loose volcanic cinders (glassy fragments of solidified lava) and ash. Also called scoria cones, they sometimes form on the sides of larger volcanoes. See also pp. 42–45.



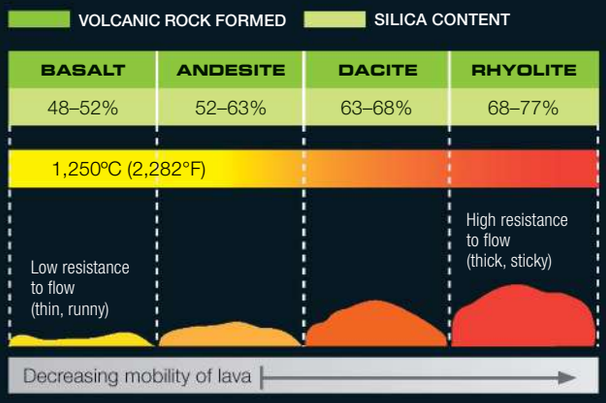
LAVA

Molten rock, or magma, that erupts onto Earth's surface from a volcano is called lava. As it spurts out it is red hot, with a temperature between 700 and 1,200°C (1,290 and 2,190°F). Although much thicker and stickier than water, lava will flow over the ground, under the influence of gravity, as long as its temperature remains high enough. Eventually it cools to form a solid rock.



LAVA PROPERTIES

Different volcanoes produce different types of lava, which vary in temperature and composition, particularly their silica content. These properties affect how far the lava can flow. The hottest lavas, with the lowest silica content, are basaltic lavas and are quite runny. They can travel for tens of kilometres, even on gentle slopes, before solidifying to basalt. These lavas come in two main forms, called pahoehoe and ʻaʻa (see below). Andesitic lavas are cooler, more flow resistant, and can travel only short distances before solidifying. Dacitic and rhyolitic lavas make up a third group. They are the least fluid and form only slow-moving flows. They cool to form rocks called dacite and rhyolite.



RANGE OF CHARACTERISTICS
From left to right, this chart shows lava with increasing silica content and viscosity (flow resistance), and decreasing temperature. Because it is relatively runny, the basaltic-type lava on the left can flow greater distances than the types on the right.



LAVA ROCK
Rocks formed from cooled lava, such as this basalt, are mostly fine grained, with small crystals, because the cooling was rapid.



ROCK FROM COOLED MAGMA
Igneous rocks formed underground, such as this peridotite, are usually coarse grained, with large crystals, because they come from magma that cooled slowly.



LAVA FOUNTAIN
Jets of lava sprayed forcefully, but not explosively, into the air are called lava fountains. They commonly occur in Hawaiian-style eruptions (see pp.70-71).



PAHOEHOE

Composition	Basaltic
Temperature	1,093–1,204ºC (2,000–2,200ºF)
Speed of advance	up to 10kph (6mph) (higher in channels)
Type	Shield volcanoes

Pahoehoe advances as a series of lobes, called toes. As its surface cools, it develops a thin, pliable skin, under which hot material streams. As the skin congeals it develops a rope-like texture.



ʻA'A

Composition	Basaltic
Temperature	982–1,093ºC (1,800–2,000ºF)
Speed of advance	5–100m/hour (15–330ft/hour)
Type	Shield and stratovolcanoes

ʻA'a is cooler and more flow-resistant than pahoehoe. Streams of ʻa'a have extremely rough, fragmented surfaces. They can advance rapidly and are capable of pushing down houses and forests.



PILLOW LAVA

Composition	Basaltic, andesitic
Temperature	871–1,204ºC (1,600–2,200ºF) (interior)
Speed of advance	1–9m/hour (3–30ft/hour)
Type	Underwater volcanoes

Pillow lava occurs when a volcano erupts underwater. On contact with water, the lava solidifies as a pillow-shaped rock. Later, pillow lava may be exposed on dry land (as above) if the seabed is raised up.



BLOCK LAVA

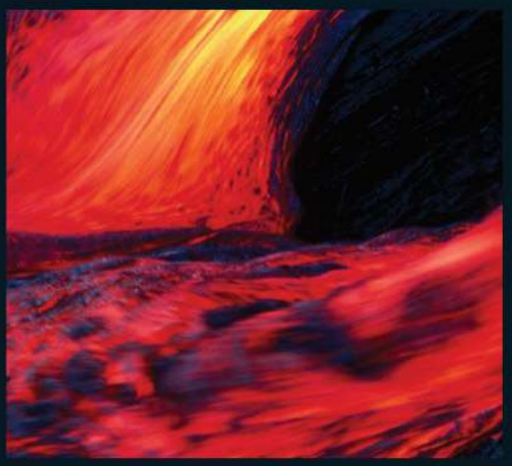
Composition	Andesitic, rhyolitic
Temperature	760–927ºC (1,400–1,700ºF)
Speed of advance	1–5m/hour (3–15ft/day)
Type	Stratovolcanoes, lava domes

Relatively cool and flow-resistant, block lava advances slowly and produces short and stubby flows. When solidified (as above), it forms roughly cube-shaped lumps of rock with relatively smooth surfaces.





FRESHLY ERUPTED LAVA
Flows of freshly erupted molten lava, some of it surface-solidified (black), advance across a crater on the Hawaiian volcano Kilauea. Underneath is an older lava crust (grey), part of which, in the foreground, has just collapsed downwards.



FAST-MOVING FLOW
This long-exposure photograph shows fast-flowing pahoehoe lava. On a moderate slope, as here, pahoehoe can attain speeds of 50kph (30mph) or faster.



MEETING THE SEA
Steam rises as the lava reaches the coast of Hawaii's Big Island. All the land here is made of black, solidified lava, the flows of which continually extend the island.



SOLIDIFIED PAHOEHOE
This pahoehoe lava produced by the Piton de la Fournaise volcano on Réunion Island, Indian Ocean, took on a typical rope-like texture as it solidified.

AERIAL PRODUCTS

Other than molten lava flowing out over the ground, the main products of eruptions are gases – some of them poisonous – and solid particles produced from magma and rock that has been blasted into the air. Each can pose hazards to people near and far.

SOLID PRODUCTS

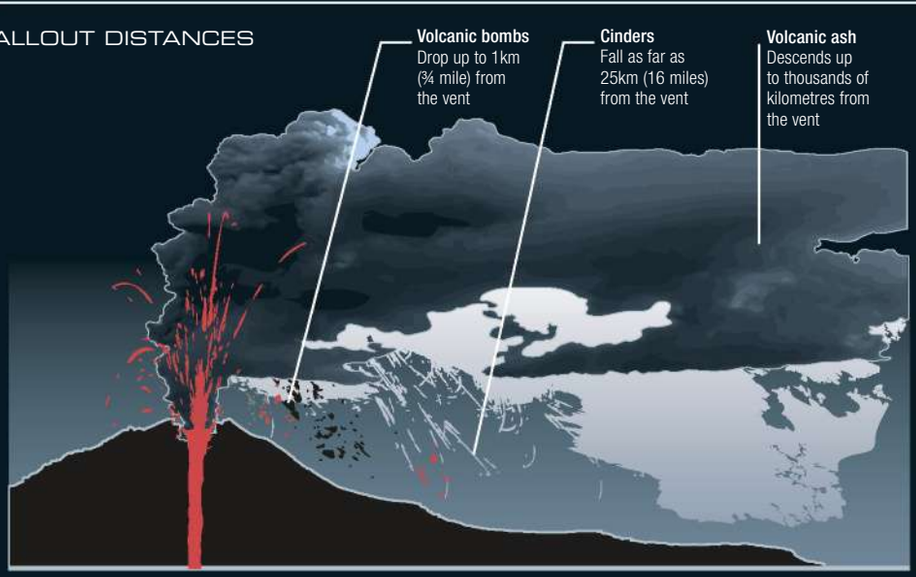
The solid products that originate from materials hurled into the air by a volcano are referred to as tephra. They come in a range of sizes. The larger pieces are volcanic bombs – blobs of magma (molten rock) that solidified as they fell – and chunks of a rock called pumice, which forms from magma blown into the air as a froth containing gas bubbles. Medium-sized fragments are called cinders, while the smallest make up volcanic ash. Although much of this smaller-sized material comes from finely fragmented and solidified magma, in violent eruptions some of it comes from pre-existing hardened lava around the volcano's vent, sometimes from deep within the volcano that is blasted skywards with the hot magma.

Tephra pose a varying degree of danger to people in eruption zones. Volcanic bombs are a hazard because of their size. Very heavy ash falls can cause death by suffocation, and combined with torrential rain can result in dangerous mudflows, while wet ash on house roofs is heavy and can lead to collapse. Inhaling even tiny amounts can cause problems for people with respiratory illnesses. Cinders are less of a danger, although if you are in the cinder zone (see below) you are at risk of being hit by falling cinders, which can burn or cause head injuries.

VOLCANIC GASES

Gases given off during volcanic eruptions include water vapour, nitrogen, and various asphyxiating, poisonous, or irritant gases such as carbon dioxide, carbon monoxide, and sulphur dioxide. The harmful gases pose the greatest hazard close to the volcanic vent, where concentrations are greatest. Rarely they can be of imminent danger to people living downwind of the eruption. Eruptions of carbon dioxide from volcanoes have, occasionally, caused mass human deaths from asphyxiation. In addition, volcanic gases cause air pollution. Sulphur dioxide reacts with moisture in the air to form acid rain, which is damaging to vegetation and a health hazard for the elderly and infirm.

FALLOUT DISTANCES



Different types of tephra tend to fall to the ground at varying distances from the site of the eruption, due to their different size ranges and susceptibility to being transported in the wind. The heaviest, volcanic bombs, drop closest to the volcanic vent, usually within a kilometre. The next heaviest, cinders, can fall further away. The lightest, volcanic ash, may be carried for tens, hundreds, or thousands of kilometres, depending on wind strength. In 1883, ash from the eruption of Krakatau, in what is now Indonesia, eventually fell to the ground all around the world.



HOT ASH
The eruption of Iceland's Eyjafjallajökull volcano in 2010 led to the cancellation of aircraft flights due to the large concentration of tiny glassy fragments it threw into the atmosphere.





CINDERS

Also called lapilli, cinders are solid particles between 2mm (1/10 in) and 6.4cm (2½in) in diameter. Often teardrop or button shaped, they fall in showers, sometimes welding together as they hit the ground.



LAVA BOMBS

These blocks and bombs of lava can be anything from 6.4cm (2½in) in diameter to boulder sized. The larger ones are solid on the outside but still molten in the centre as they hit the ground.



VOLCANIC ASH

The smallest particles – less than 2mm (1/10in) in diameter – are carried into the atmosphere as a plume that can interfere with aviation. Where the ash eventually falls, it forms a dust-like layer.



LIGHTNING

Lightning flashes occur commonly in volcanic ash plumes, due to friction between ash-laden cloud and the normal atmosphere. The combination of ash and lightning is called a “dirty thunderstorm”.



VOLCANIC GASES

During eruptions, gases that were dissolved in magma are released. These gases typically have a temperature above 400ºC (752ºF). Gases are also released from magma that remains below ground.



PELÉ’S HAIR

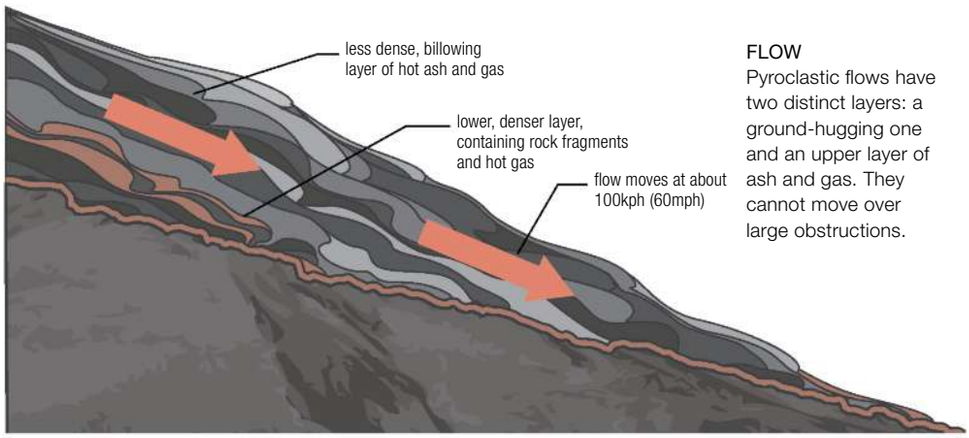
This curious, yellow-coloured material is formed when airborne particles of magma are spun by the wind into glassy, hair-like strands. It is named after Pelé, the Hawaiian goddess of volcanoes.

PYROCLASTIC FLOWS AND SURGES

One of the most dangerous phenomena associated with a volcanic eruption are those that produce pyroclastic flows – hot, fast-moving, ground-hugging mixtures of ash, rock, and hot gas. Just as devastating are related events called pyroclastic surges.

FLOWS

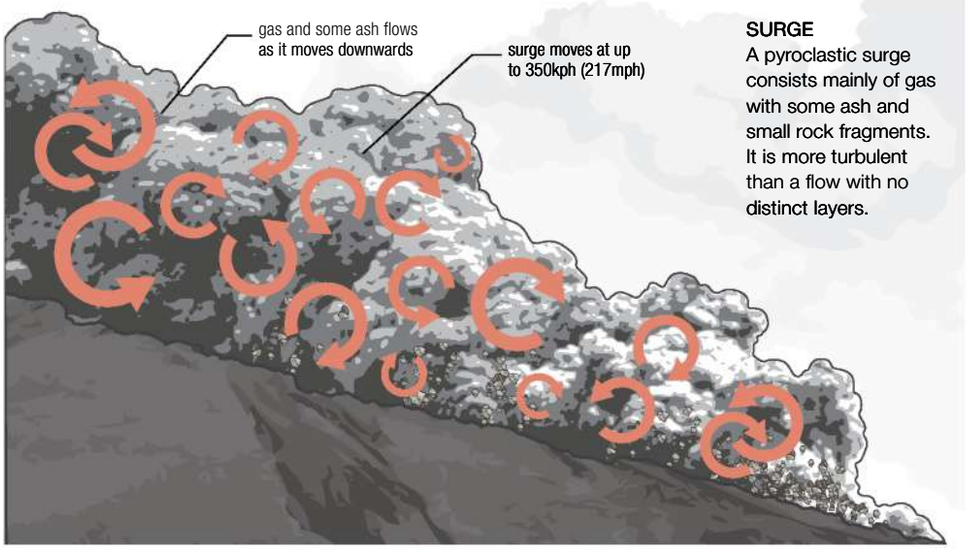
Also known as *nuées ardentes* (glowing clouds), pyroclastic flows flatten, burn, and bury everything they encounter. Most travel for about 5–10km (3–6 miles). They are most often caused by the collapse of an ash column following a large eruption. Normally, the erupted ash heats the surrounding air, and the ash-gas mixture rises by convection. However, if the air hasn't heated up sufficiently, both ash and gas fall back down the flanks of the volcano. Other causes include eruptions in which a large lateral blast comes from the side of a volcano, a large lava dome at the volcanic vent collapses, or a thick, slowly moving lava flow front collapses.



FLOW
Pyroclastic flows have two distinct layers: a ground-hugging one and an upper layer of ash and gas. They cannot move over large obstructions.

SURGES

Surges contain a higher proportion of gas to rock and are faster than pyroclastic flows. Hot surges contain gas and steam at temperatures of 100–800°C (212–1,472°F). Cold ones usually have a temperature below 100°C (212°F) and are produced when magma comes into contact with a large quantity of water known as a phreatomagmatic eruption. They often contain poisonous gases.



SURGE
A pyroclastic surge consists mainly of gas with some ash and small rock fragments. It is more turbulent than a flow with no distinct layers.



COLLAPSING ASH CLOUD
A searing combination of hot gas and ash roars downhill during an eruption of the Soufrière Hills volcano on the Caribbean island of Montserrat.



AFTER THE PYROCLASTIC FLOW
These houses on Montserrat were blasted and buried by a pyroclastic flow following the eruption of the Soufrière Hills volcano in June 1997.

ENVIRONMENTAL IMPACT

Pyroclastic flows and surges incinerate all vegetation they encounter, devastating huge areas. A pyroclastic flow from Mount St Helens in 1980, which impacted an area of 600 sq km (230 sq miles) previously covered by dense forest, left not a single plant alive. Thousands of large mammals and millions of fish and birds were also wiped out. Areas affected by these events can take decades to recover, though encouragingly, they eventually do so.

HUMAN IMPACT

Pyroclastic flows from Mount Lamington in Papua New Guinea in 1951, killed almost 3,000 people, while those from El Chichón volcano in Mexico in 1982, caused 2,000 fatalities. As well as destroying buildings, pyroclastic events kill people through a combination of burning, asphyxiation, and poisoning. They have been implicated in some of the deadliest volcanic eruptions in recorded history, for example, the 4,000 killed by an eruption from Vesuvius in 1631 and 30,000 killed in a matter of minutes in Martinique in 1902 (see p.79). As well as causing high numbers of fatalities, pyroclastic flows and surges can also result in a huge burden of injury and illness, ranging from severe burns to respiratory problems from ash inhalation.



PYROCLASTIC FLOW
Photographers who had been observing the 1991 eruption of Mount Pinatubo in the Philippines fled from a huge pyroclastic flow bearing down on them. The eruption killed several hundred people, but the occupants of this truck – and the person who was photographing them – escaped.



VOLCANIC MUDFLOWS

Also called "lahars", volcanic mudflows are violent, fast-moving slurries of water, ash, rocks, and other debris, resembling flowing wet concrete, that – in response to various triggering factors – may surge down the flanks of a volcano. Large flows can rip trees out of the ground, transport boulders the size of houses, sweep away buildings and people, and bury extensive areas of land in thick mud.

OCCURRENCE

Lahars can be set off by anything that causes large quantities of water to become mixed with ash and other debris on a volcano. Scenarios include eruptions from water-filled volcanic craters, torrential storms, rainfall on fresh ash deposits, and eruptions or earthquakes causing glaciers around a volcano's summit to disintegrate and melt. Lahars can also result from pyroclastic flows (see pp.28-29) running into mountain lakes or melting glacier ice. Large lahars move at up to 100km (60 miles) per hour. They can surge for tens of kilometres along river valleys at the base of a volcano, leaving mud deposits several metres thick in their wake. These deposits quickly congeal, making it difficult for anybody trapped in them to escape.

Deadly lahars have affected many parts of the world historically. In May 1919, for example, lahars from the Kelut volcano in Indonesia killed more than 1,500 people. Other examples include a lahar in Nicaragua that killed more than 1,500 people in 1998, triggered by hours of intense rainfall onto the Casita volcano.

> "WE WERE SWEPT ALONG, IN OUR CAR, FOR ABOUT FIVE MINUTES IN THICK WARM MUD."
>
> **EYEWITNESS** CAUGHT UP IN A LAHAR TRIGGERED BY THE 1980 MOUNT ST HELENS ERUPTION



MUDFLOW ON SOUFRIÈRE HILLS
This mud deposit was left on the western flank of the Soufrière Hills volcano, on the Caribbean island of Montserrat, following an eruption in 2006. Soufrière Hills has been erupting on and off since 1995, often producing pyroclastic flows and lahars.



EMERGENCY AID
Apart from any fatalities caused, volcanic mudflows often leave huge numbers of people injured or homeless – 24,000 in the case of the Nevado del Ruiz disaster – and fast provision of aid is essential.

NEVADO DEL RUIZ

The most deadly lahars in history followed an eruption of the Nevado del Ruiz volcano in Colombia in November 1985. Pyroclastic flows interacted with extensive glaciers covering the volcano's summit, triggering massive slurries of mud that surged down the side of the volcano. Heavy rain had recently fallen over the whole region, so the lahars took in enormous amounts of additional water and rock debris from river channels as they descended. This increased their volume and momentum. Worst hit was the town of Armero, where more than 23,000 people were either drowned or asphyxiated by burial in mud. Armero became the focus of the disaster because it was located at a depression in the landscape just downstream from where two lahars flowed into each other. The economic cost of the disaster was estimated at $7.7 billion. Today, a lahar warning system is in place in the region.

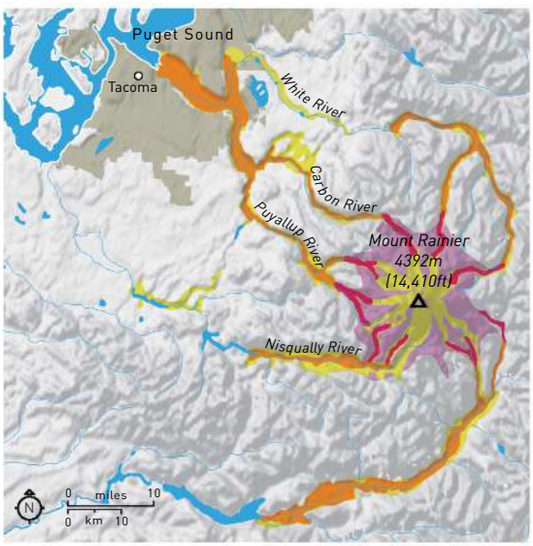
THE MOUNT RAINIER THREAT

Some of the world's volcanoes have been identified as the source of large historic lahars, and a potential source of future ones. Mount Rainier, a large stratovolcano in Washington State, USA, is one example of this. Although it hasn't erupted since 1894, Mount Rainier has several large glaciers on its upper slopes, which, if they disintegrated and melted, could cause catastrophic lahars. About 5,600 years ago, the largest known lahar at Mount Rainier, the Osceola Mudflow, surged more than 100km (60 miles) across Washington to reach areas on which parts of the city of Tacoma, and other communities to the south of Seattle, are now built. Deposits from this lahar extended over more than 550 sq km (212 sq miles) of northwestern Washington and produced mud deposits that were 80m (262ft) deep in places. Other smaller mudflows have flowed from Mount Rainier since then, and about 150,000 people live in communities that are built on old lahar deposits. If, as is possible, another lahar of comparable size to the Osceola Mudflow were to occur, it would bury a number of these towns and might even reach the centre of Seattle.

To protect the population around Mount Rainier, a lahar warning system was installed in 1998. Seismometers are placed at various locations around the volcano to sense tremors that might indicate the start of a large mudflow. Alarms caution people to move to higher ground until the danger has passed.



ARMERO DESTROYED
As a result of lahars from Nevado del Ruiz in 1985, 5,000 homes were destroyed in this town in central Colombia. Thousands were killed by a thick wall of mud that arrived in the dead of night.



KEY

- Small lahars with recurrence interval of less than 100 years
- Moderate lahars with recurrence interval of 100–500 years
- Large lahars with recurrence interval of 500–1,000 years
- Area most likely to be affected by lava flows and pyroclastic flows
- Urban areas

LAHAR PATHS
This map of Mount Rainier and the surrounding region shows the paths of some historic lahars, which are also believed to be the most likely routes for future possible large mudflows.

CONTINENTAL VOLCANIC ARCS

All around the eastern and northern Pacific Ocean, where the edges of oceanic lithospheric plates push down beneath continents, some impressive arrays of volcanoes have formed inland on the continental sides of the plate boundaries. These are known as continental volcanic arcs.

CENTRAL AMERICAN ARC

The Pacific coastline of Central America is marked by a chain of more than 50 active volcanoes. This chain extends for 1,500km (900 miles), from Guatemala to western Panama. As with all continental volcanic arcs, these volcanoes have formed tens of kilometres inland from the coast and run parallel to it. They were created when the Cocos Plate on the west subducted beneath the Caribbean Plate on the east. This volcanic chain has produced some colossal eruptions in the past, including an eruption of Guatemala's Santa María volcano in 1902, which was one of the four largest of the 20th century.

ANDEAN VOLCANIC BELT

In western South America, intermingled with many non-volcanic mountains, lies an interrupted chain of almost 200 volcanoes that were created by the Nazca and Antarctic Plates pushing beneath the South American Plate. Diverse in forms and activity, these volcanoes fall into four arcs, or zones. The first stretches across Colombia and Ecuador (northern arc), the second between southern Peru, southwestern Bolivia, and northern Chile (central arc), the third in Chile (southern arc), and the fourth in southern Chile and Argentina (austral arc). Many of these volcanoes pose a major hazard as they lie in densely populated regions.





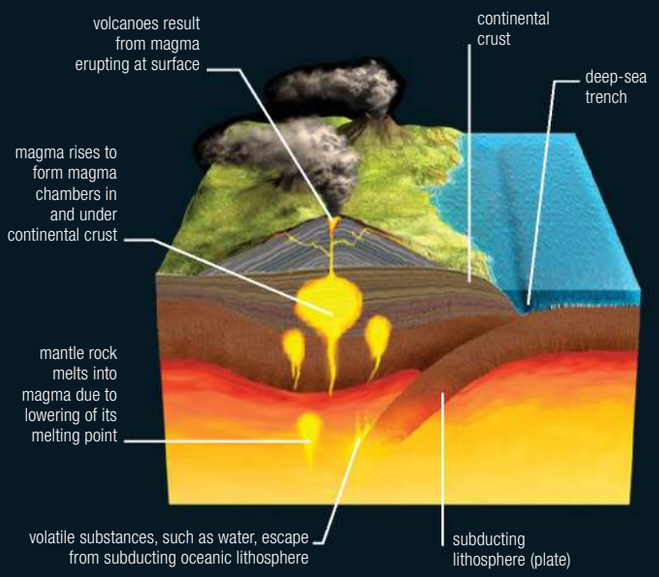
FOUR STRATOVOLCANOES
Four volcanoes in El Salvador, called Usulután, El Tigre, Chinameca, and San Miguel (left to right), lie near the middle of the Central American Arc. San Miguel last erupted in 2002.

ON THE BORDER
These two stratovolcanoes, called Licancabur and Juriques, are close to the southern end of the Chile–Bolivia border, within the central zone of the Andean volcanic belt.

KAMCHATKA VOLCANIC ARC

About 30 volcanoes are situated along the Kamchatka Peninsula in eastern Russia. They occur above a region where the Pacific Plate descends beneath the Okhotsk Plate. Like all continental volcanic arcs, the Kamchatka consists mainly of stratovolcanoes, many of which can erupt violently. However, because of the sparse population of the region, they are not a major threat to human life. The peninsula contains Kliuchevskoi, the tallest active volcano in Europe and Asia, which regularly emits ash plumes to 6.000m (19,000 ft) or higher. Its most active volcano is Karymsky, which has been erupting continuously since 1996.

KLIUCHEVSKOI AND NEIGHBOURS
The symmetrical volcano in the foreground is Kliuchevskoi, with neighbours Kamen on the left and Ushovsky on the right.



VOLCANO FORMATION

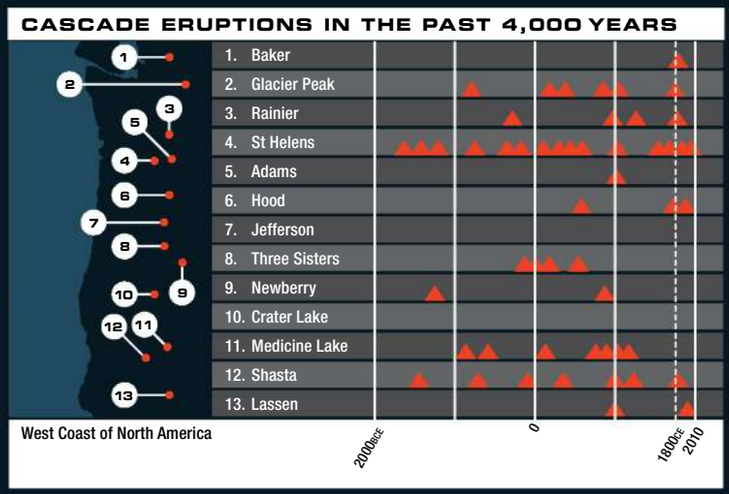
At plate boundaries, where the oceanic lithosphere is drawn down, or subducted, beneath the continental lithosphere, magma forms and leads to the creation of volcanoes. This process is thought to always occur in the same way. At depth, water and other volatile substances escape from the subducting oceanic lithosphere into the mantle region beneath the neighbouring continent. There, the presence of these volatile substances acts as a flux and lowers the melting point of the mantle rocks. As a result, the mantle rocks melt to form magma – the hot, molten combination of melted rock and gases. This rises up to form magma chambers within the overlying continental crust. From these chambers, the magma erupts onto the surface to form volcanoes.

MAGMA FORMATION

The key process in the formation of continental volcanic arcs is the melting of mantle rocks at depth, which occurs when volatile substances escape from the subducting plate.

CASCADE VOLCANIC ARC

One of North America's arcs is known as the Cascade Volcanic Arc, or the Cascade Range. This chain of about 20 snow-capped volcanoes extends north for more than 1,100km (680 miles), from northern California, through Oregon and Washington, and into British Columbia (Canada). It includes well-known peaks such as Mount St Helens and Mount Rainier in the USA, and Mount Garibaldi in Canada. Many of these volcanoes are potentially dangerous, as they lie close to highly populated areas, such as Portland, Seattle, and Vancouver. They occur above a region where the Juan de Fuca Plate, a small tectonic plate in the northeastern Pacific, was subducted beneath the North American Plate. Of these volcanoes, Mount St Helens has experienced the most eruptions, most recently in 2008 (see pp.86-87).



CASCADE ERUPTIONS

This chart of Cascade Volcanoes within the USA shows that although only Mount St Helens and Mount Lassen have erupted in very recent times, many others have done so repeatedly in the past 4,000 years.

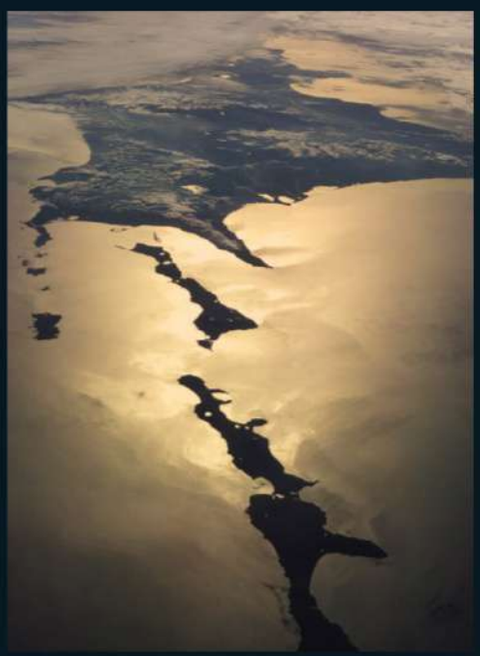


VOLCANIC ISLAND ARCS

At numerous plate boundaries around the world, slabs of oceanic lithosphere on separate plates come together, or converge, with the edge of one plate subducting beneath its neighbour. The result is both a deep trench on the sea floor, and a gently curving line, or arc, of volcanic islands formed about 200km (125 miles) from the trench and parallel to it. These lines of islands are called volcanic island arcs.

ARC FORMATION

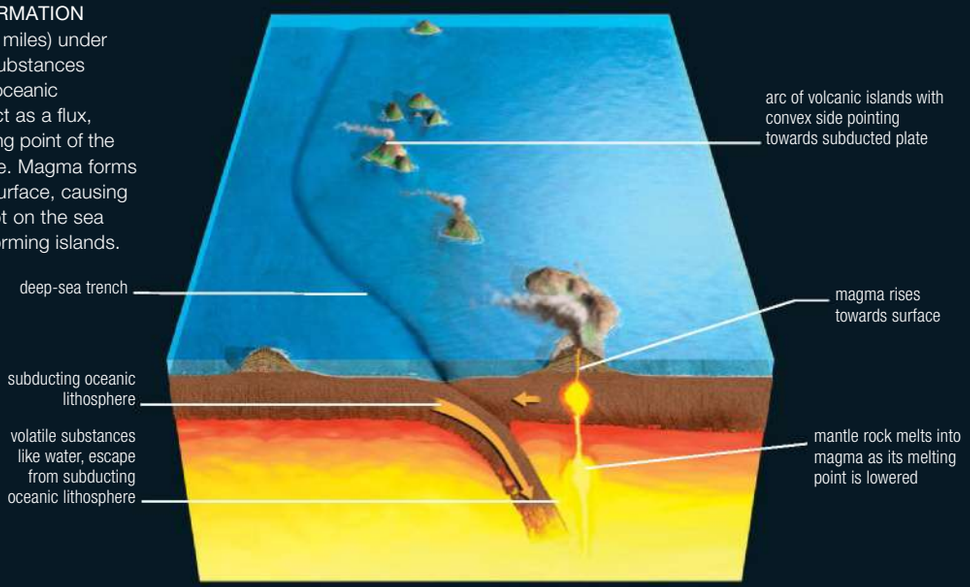
As in continental volcanic arcs, volcanic island arcs occur when magma forms at depth, close to the descending plate (see p.35), and then rises up to erupt at the surface. In an all-oceanic setting, the only difference is that the magma erupts onto the sea floor, eventually forming an arc of volcanic islands. A classic example is the Lesser Antilles Arc, which formed when the North and South American Plates subducted under the Caribbean Plate. It consists of a dozen small islands stretching in a perfect curve across the eastern Caribbean. Some of these have produced lethal eruptions over the past 200 years. Another, the Sunda Arc, was caused by the Australian Plate pushing beneath the Eurasian Plate. This arc includes many of the main islands of Indonesia. In this case, more than 70 distinct volcanoes have joined together to form the cores of two very large islands, Java and Sumatra, and many smaller ones. The Sunda Arc includes the notorious volcanoes Tambora and Krakatau, responsible for two of the most violent, lethal eruptions in history.



STRING OF ISLANDS
This view from space shows some of the Kuril Islands along with the Japanese Island of Hokkaido in the background. Both are parts of volcanic island arcs.

> "VOLCANOES FORM NO EXCEPTION TO THE PRINCIPLES OF UNIVERSAL ORDER."
>
> **JOHN KENNEDY**, *VOLCANOES: THEIR HISTORY, PHENOMENA, AND CAUSES*, 1852

ISLAND ARC FORMATION
About 100km (60 miles) under the sea, volatile substances escape from the oceanic lithosphere and act as a flux, lowering the melting point of the mantle rock above. Magma forms and rises to the surface, causing volcanoes to erupt on the sea floor, eventually forming islands.







LESSER ANTILLES ARC
This Caribbean arc is about 850km (530 miles) long. Nearly every island has a volcano, with Dominica having nine.



ONEKOTAN ISLAND
Part of the Kuril Island Arc, which stretches between northern Japan and Russia's Kamchatka Peninsula, Onekotan Island consists of two connected volcanoes. The larger, Tao-Rusyr, is a caldera with a central crater lake, within which a small stratovolcano is growing. The other is Nemo Peak, which last erupted in 1938.

PACIFIC ARCS

Other than the Lesser Antilles and Sunda Arcs, most volcanic island arcs are situated around the edges of the Pacific – making up a large part of the Pacific Ring of Fire (see pp.124–125). One of the longest, the Aleutian Island Arc, lies in the Northern Pacific, where the Pacific Plate subducts beneath the North American Plate. To its southwest lies the Kuril Island Arc, and continuing to the southwest, the islands of Japan, which are themselves a volcanic arc. Further south is the 750-km- (470-mile-) long Mariana Arc, lying approximately 180km (110 miles) to the west of the Mariana Trench, the deepest of all deep-sea trenches. Numerous other Pacific island arcs include the Japanese Izu and Ryukyu Islands, the Philippines, the Solomon Islands, and Vanuatu. Another example is the Bismarck Volcanic Arc, off the northeast coast of Papua New Guinea, which contains the dangerous volcanoes Ulawun and Rabaul.



RABAUL CALDERA
A flooded caldera, Rabaul is the easternmost volcano in the Bismarck Arc. It has two stratovolcanoes at its edge, one of which, Tavurvur, is visible here. A combined eruption from the two stratovolcanoes in 1937 killed more than 500 people.

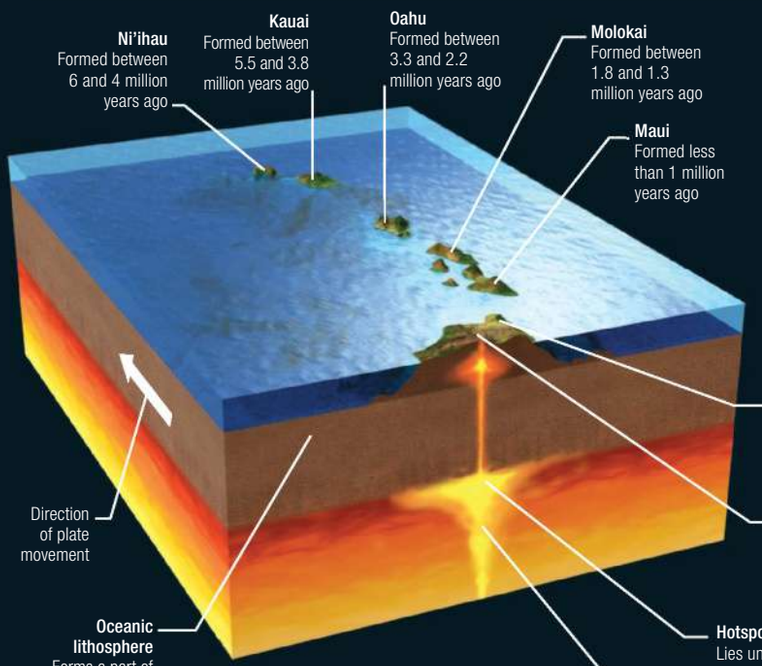
VOLCANIC ISLAND CHAINS

If a plate consisting of oceanic lithosphere gradually moves over a hotspot at the top of the mantle, it can create a chain of islands. It is usual to find a volcano – or volcanoes – energetically building an island above the hotspot location, while the rest of the chain displays evidence of the past volcanic activity of the same hotspot.

HAWAIIAN CHAIN

The Hawaiian chain in the central Pacific is a classic example of a volcanic island chain. The Big Island of Hawaii – in particular its two large active volcanoes, Mauna Loa and Kilauea, and a young submarine volcano off Hawaii's south shore called Loihi – stands over a strong, active, and persistent hotspot under the Pacific Plate. Stretching away in a line to the northwest from the Big Island are other substantial islands. Beyond these are smaller islands, atolls, reefs, and submerged seamounts – mostly extinct submarine volcanoes – stretching out for 2,500km (1,500 miles) to a location called Kure Atoll. The whole chain is thought to have been created during the course of the past 30 million years as the Pacific Plate moved over a hotspot. A number of other volcanic chains in the central and southern Pacific, such as the Tuamoto Archipelago, show a similar pattern.

> "...WE ARE LED TO BELIEVE THAT WITHIN A PERIOD GEOLOGICALLY RECENT THE UNBROKEN OCEAN WAS HERE SPREAD OUT."
>
> **CHARLES DARWIN**, IN *THE VOYAGE OF THE BEAGLE*, 1845, REFERRING TO THE RELATIVELY RECENT ORIGIN OF THE GALÁPAGOS ISLANDS



AGE OF HAWAIIAN ISLANDS
As per the hotspot theory, the islands of the Hawaiian chain are progressively older the farther they are located from the hotspot.

GALÁPAGOS ISLANDS

The Galápagos Archipelago is a group of volcanic islands that lie on the Nazca Plate in the eastern Pacific. They are thought to have formed because of the eastward movement of the Nazca Plate over a persistent hotspot. Unlike the simple pattern of the Hawaiian chain, the Galápagos hotspot has produced several lines of volcanoes that have formed over the past 5–10 million years. This complex formation has been attributed to the location of the Galápagos – it is close to a mid-ocean spreading ridge, where new plate is created. Varying activity at this ridge may have led to the unusual grouping of these islands.



GALÁPAGOS CRATERS
Signs of recent or past volcanic activity, caused by the presence of the Galápagos hotspot, can be seen all over the Galápagos Islands. The central volcanic crater here is named Beagle, after the ship that carried Charles Darwin to the islands in 1835.

HAWAIIAN ISLAND CHAIN
This 3-D model shows five Hawaiian Islands, including Maui and Oahu, that are the visible peaks of a continuous, volcanically created, mostly submarine massif.

INDIAN OCEAN VOLCANIC CHAIN

One of the most remarkable volcanic chains believed to have been caused by a hotspot lies in the Indian Ocean. About 67 million years ago, plate movements are thought to have led India to pass over the hotspot, resulting in the formation of thick lava flows that make up the Deccan Traps. Later, as the Indian Plate moved in a northeasterly direction, more volcanic islands were created in the Indian Ocean. About 30 million years ago, a mid-ocean ridge passed over the same hotspot. Since then, the hotspot has been located under the African Plate, which has moved relative to the hotspot in a roughly easterly direction. After a period of quiet, the hotspot created more islands, including Mauritius and, most recently, Réunion.





KEY

- Mid-ocean ridge
- Hotspot track
- Presumed track of hotspot during quiescent phase

HOTSPOT TRACK
Over the past 67 million years, plate movements over the hotspot currently under Réunion are thought to have created the Deccan Traps, the Maldives, the Chagos Archipelago, Mauritius, and Réunion itself.

MORNE BRABANT, MAURITIUS
Mauritius shows many signs of past volcanism, including this large basaltic rock called Le Morne Brabant, probably caused by the Réunion hotspot.

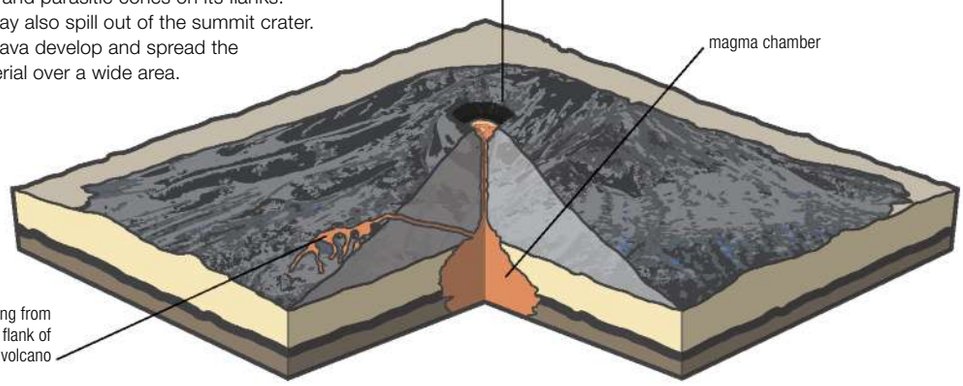
SHIELD VOLCANOES

Shield volcanoes are broad, shield-shaped volcanoes formed from multiple layers of runny lava that erupted from the volcano, flowed over its flanks, and solidified. Shield volcanoes are limited in number and are found in most areas of the world but are most common in locations such as Hawaii, Iceland, the Galápagos Islands, and the East African Rift Zone.

STRUCTURE AND FORMATION

Shield volcanoes form in places where magma with a basaltic composition rises and erupts as lava at the surface. This typically occurs where there is a hotspot beneath the crust – such a hotspot may be under oceanic crust, under a mid-ocean ridge, or under a continental rift zone. Basaltic lava is very fluid and can flow a long distance before it solidifies, which accounts for the broad shape of these volcanoes. Although some shield volcanoes are extinct, others undergo almost nonstop Hawaiian-style eruptions. In these eruptions, copious amounts of lava are quietly spouted out onto the surface, but in rare cases there have been huge explosions or ash columns.

SHIELD VOLCANO ERUPTION
During an eruption, runny lava is spewed onto the volcano's surface, often in the form of lava fountains, from fissures and parasitic cones on its flanks. Some lava may also spill out of the summit crater. Channels of lava develop and spread the erupted material over a wide area.





FERNANDINA
This massive shield volcano occupies the whole of the island of Fernandina, the youngest and most volcanically active of the Galápagos Islands. At its summit is a partially collapsed caldera about 6km (4 miles) wide and several hundred metres deep. Fernandina's last major eruption was in 2009.



ERUPTING CONE ON KILAUEA
Lava is seen here fountaining out of a secondary, or parasitic, cone on the flank of Kilauea, a shield volcano in Hawaii. Kilauea is one of the world's most active volcanoes – it has been erupting continually since 1983.



LAVA LAKE
The summit of Erta Ale in Ethiopia contains pits that are often filled with lava lakes. The lake surface seen here has a dark skin of solid lava, but splits have appeared in it, revealing the searingly hot, bright, molten lava underneath.



DISTINCTIVE FEATURES

At the summit of a shield volcano is a wide crater sometimes in the form of a caldera, which may be partially collapsed. In a few, the summit crater contains one or two pits that contain lakes of red-hot lava. Sometimes, where the volcano has not recently erupted, the crater may be partly filled with water. The flanks of the volcano usually slope gently and are covered in dark, solidified flows of lava. Also visible are fissures and parasitic cones, the sites of past or ongoing eruptions of lava. On some shield volcanoes, channels of flowing lava become enclosed in conduits called lava tubes. Once the lava has drained, these leave long, cave-like tunnels under the surface.



SPATTER CONES
These erupting cones, photographed on the shield volcano Piton de la Fournaise on Réunion Island in 2010, are called spatter cones. They are built from chunks of lava that were blown into the air and congealed in a heap once they hit the ground.

LARGEST ACTIVE SHIELD VOLCANOES

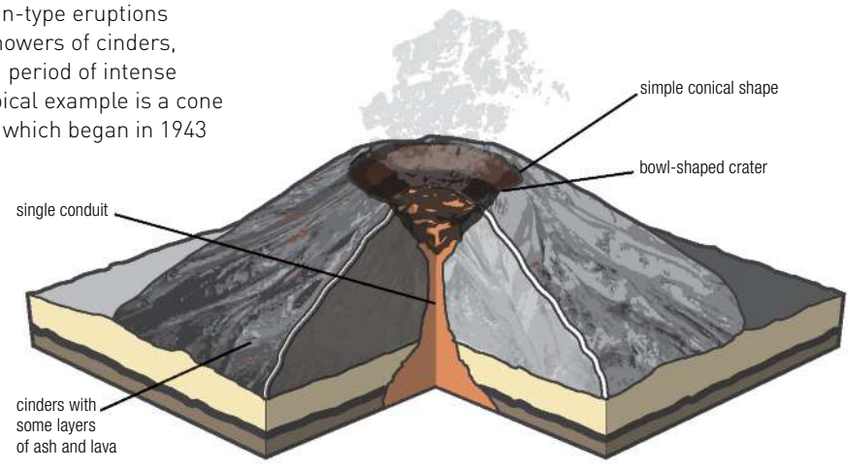
LOCATION	PROFILE	SUMMIT HEIGHT	MAXIMUM WIDTH OF BASE
Mauna Loa, Hawaii		4,169m (13,677ft)	95km (59 miles)
Erta Ale, Ethiopia		613m (2,011ft)	80km (50 miles)
Sierra Negra, Galápagos		1,500m (4,921ft)	50km (31 miles)
Nyamuragira, Democratic Republic of the Congo		3,058m (10,033ft)	45km (28 miles)
Kilauea, Hawaii		1,247m (4,091ft)	50km (31 miles)

CINDER CONES

Also called scoria cones or pyroclastic cones, cinder cones are relatively small volcanoes built mainly of loose volcanic cinders (glassy fragments of solidified lava). Some contain appreciable quantities of volcanic ash or lava. They often form on the flanks of larger volcanoes, sometimes as single cones or in groups.

FORMATION AND ERUPTION

Cinder cones often start as small fissures that suddenly appear in the ground and start spouting cinders and lava bombs. They then grow rapidly for a few months or years, producing Strombolian and Vulcanian-type eruptions (see pp.74-75 and pp.76–77), with showers of cinders, bombs, and some lava flows. After a period of intense activity they may then go quiet. A typical example is a cone known today as Parícutin in Mexico, which began in 1943 as a fissure in a cornfield. Within a year it had grown to 300m (984ft) high, but in 1952, after reaching a maximum height of 424m (1,391ft), its eruptions stopped.



CINDER CONE STRUCTURE
A cinder cone has steep sides and is built from volcanic cinders, sometimes with layers of lava and ash. At its summit is a crater from which cinders and ash are spewed out. Where lava is erupted, it tends to flow from a breach on the side of the crater.

ACTIVITY LEVEL

Most cinder cones appear, erupt and grow for a few years, and then go quiet. The many volcanoes around the world like this, which have just one main eruptive phase, are known as monogenetic. Others are polygenetic, meaning that they have more than one eruptive phase. A large cinder cone in Nicaragua called Cerro Negro, for example, has erupted more than 23 times since 1850, and poses a hazard to people living close to it today.



TAKING SAMPLES
A scientist wearing protective clothing takes a lava sample from the edge of the Pu'u 'O'o vent on Kilauea volcano, Hawaii.



SYMMETRICAL CONE
Eve cone is an almost perfectly symmetrical cinder cone, one of a group of 30 that sits on the flank of a shield volcano in British Columbia, Canada. It formed about 1,300 years ago, which in geological terms is recent. It is 172m (564ft) high and about 450m (1,476ft) wide.



GROUP OF CONES
This group of cones lies in part of a volcanically active region of northwestern Saudi Arabia, called Harrat Lunayyir. The area is close to a divergent plate boundary, marking a rift, where Arabia is moving away from Africa, thus explaining its volcanicity. More eruptions may occur in the future.



PU'U 'O'O CINDER CONE
This is a parasitic cone sitting on the flank of a much larger parent volcano, the shield volcano Kilauea in Hawaii. Pu'u 'O'o has been erupting continually since 1983, producing cinders, lava fountains and flows, and volcanic gases.



MADAGASCAN CINDER CONE
This extinct, heavily cultivated, and partially eroded cinder cone is part of the Itasy Volcanic Field. It lies near Lake Itasy in Madagascar within a volcanic region that also contains many hot springs. The last eruptions in the area took place about 8,000 years ago.

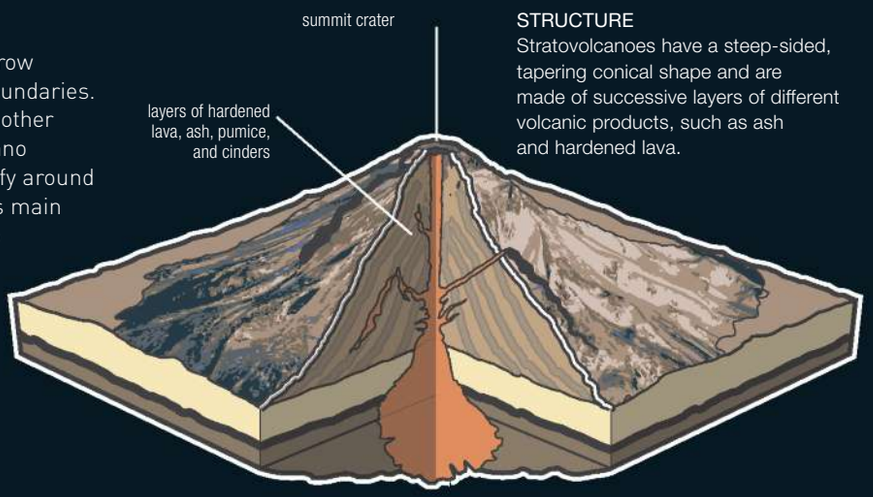


STRATOVOLCANOES

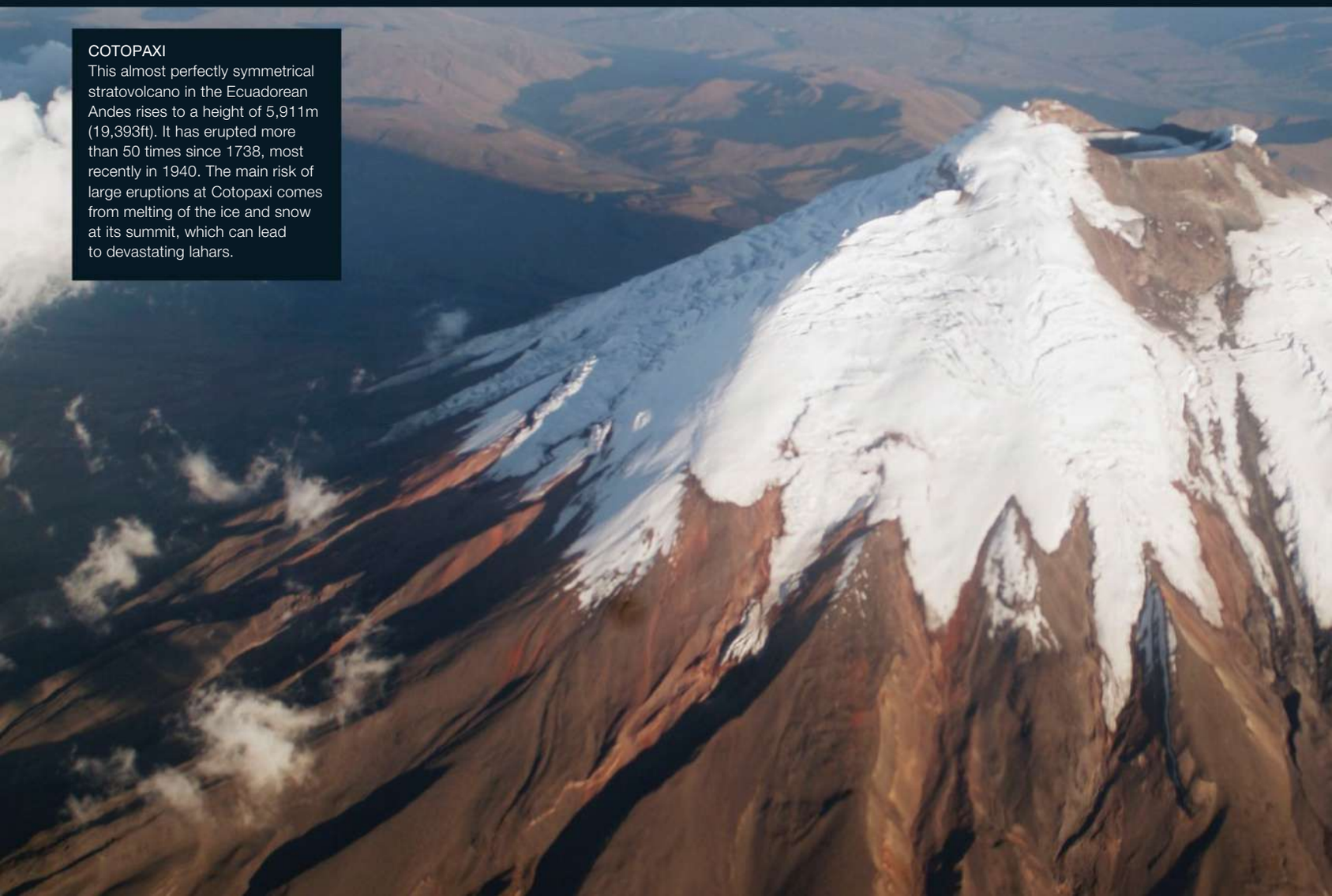
Stratovolcanoes, or composite volcanoes, are large, conical volcanoes built from layers of hardened lava and materials such as ash and cinders that are produced when magma (molten rock) is blasted into the air. They include some of the best known and most spectacular-looking – but also some of the most dangerous – volcanoes in the world.

FORMATION AND ACTIVITY

Although some stratovolcanoes develop at hotspots, most grow near ocean–continent and ocean–ocean convergent plate boundaries. In contrast to the runny lava that builds shield volcanoes (the other main type of large volcano), the lava erupted by a stratovolcano usually does not flow far. Instead it has a tendency to solidify around and within, and from time to time to block up, the volcano's main vent. As a result, much of the material that a stratovolcano erupts is not lava flowing over the surface, but tephra (cinders, ash, pumice, and volcanic bombs) produced in explosive eruptions as the volcano clears its main vent. This helps explain not only the structure of stratovolcanoes but also their long-term behaviour, with phases of violent activity interspersed with quiet periods, which can last for anything from a few years to several thousand years.



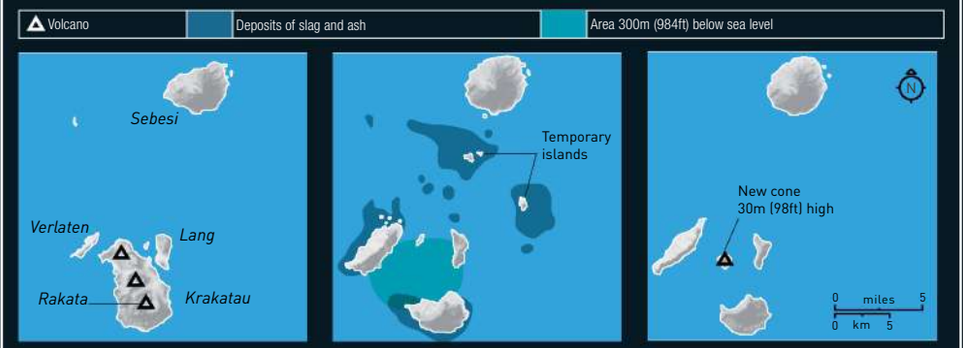
STRUCTURE
Stratovolcanoes have a steep-sided, tapering conical shape and are made of successive layers of different volcanic products, such as ash and hardened lava.



COTOPAXI
This almost perfectly symmetrical stratovolcano in the Ecuadorean Andes rises to a height of 5,911m (19,393ft). It has erupted more than 50 times since 1738, most recently in 1940. The main risk of large eruptions at Cotopaxi comes from melting of the ice and snow at its summit, which can lead to devastating lahars.

KRAKATAU: A FAMOUSLY DANGEROUS STRATOVOLCANO

One of the deadliest volcanic eruptions in history occurred in August 1883 from a stratovolcano on the island of Krakatau in Indonesia. An explosion at the end of the eruption literally blew Krakatau apart. Vast amounts of rock and ash were spewed into the atmosphere or despatched towards nearby islands in the form of pyroclastic flows, and a series of powerful tsunamis followed. According to official records, 165 towns and villages were destroyed and some 36,000 people died, mainly as a result of the tsunamis. Krakatau's final explosion is famous for being the loudest sound ever reported – it was heard distinctly in Perth, Australia, some 3,100km (1,925 miles) away.



1880 Krakatau was an island containing three coalescing volcanic cones (triangles) of which at least one, Rakata, was a stratovolcano.

1883 Much of the original island had gone, through being blown apart. New islands and underwater deposits had formed from the debris.

1927 A new stratovolcano had appeared where some of Krakatau's original cones stood. This was named Anak Krakatau or "Child of Krakatau".

CHARACTERISTICS

Stratovolcanoes can erupt in a variety of styles from relatively mild Strombolian eruptions to more dangerous Vulcanian, Peléan, or Plinian eruptions. They can produce a range of effects from showers of lava bombs and cinders, accompanied by loud explosions, to huge ash clouds and pyroclastic flows. Due to the high altitude of their summits, many stratovolcanoes carry large glaciers or snowfields on their upper slopes, which pose the risk of dangerous lahars (mudflows) when an eruption occurs. Eruptions can last for anything from a few hours or days to many tens of years. Many of the most destructive eruptions of the past have come from stratovolcanoes, including Krakatau.





ARENAL ERUPTION
This young stratovolcano in Costa Rica has been erupting regularly since 1968, after centuries of inactivity. In recent years, glowing fountains and streams of lava have been visible almost every night.



MOUNT RUAPEHU ERUPTING
The largest active volcano in New Zealand, Ruapehu erupted spectacularly in 1996, producing a tall dark ash plume. A later euption in 2007 triggered a powerful lahar.

ETNA

Europe's largest volcano, Etna covers 1,190 sq km (460 sq miles) of eastern Sicily. Standing at 3,329m (10,922ft) high, it is a stratovolcano with a complex structure that includes four separate summit craters and more than 300 smaller parasitic vents and cones on its flanks. Etna started forming 500,000 years ago on the floor of the Mediterranean and emerged from the sea about 100,000 years ago. Over the past several thousand years, it has been almost continuously active, producing eruptions of two main types. Spectacular explosive eruptions, from one or more of its summit craters, produce volcanic bombs, cinder showers, and large ash clouds. Etna also has Hawaiian and Strombolian-type eruptions (see pp.70-75) from vents and fissures on its flanks. These eruptions typically feature lava fountains and extensive flows of runny basaltic lava, which can be either pahoehoe or ʻaʻa (see p.23).



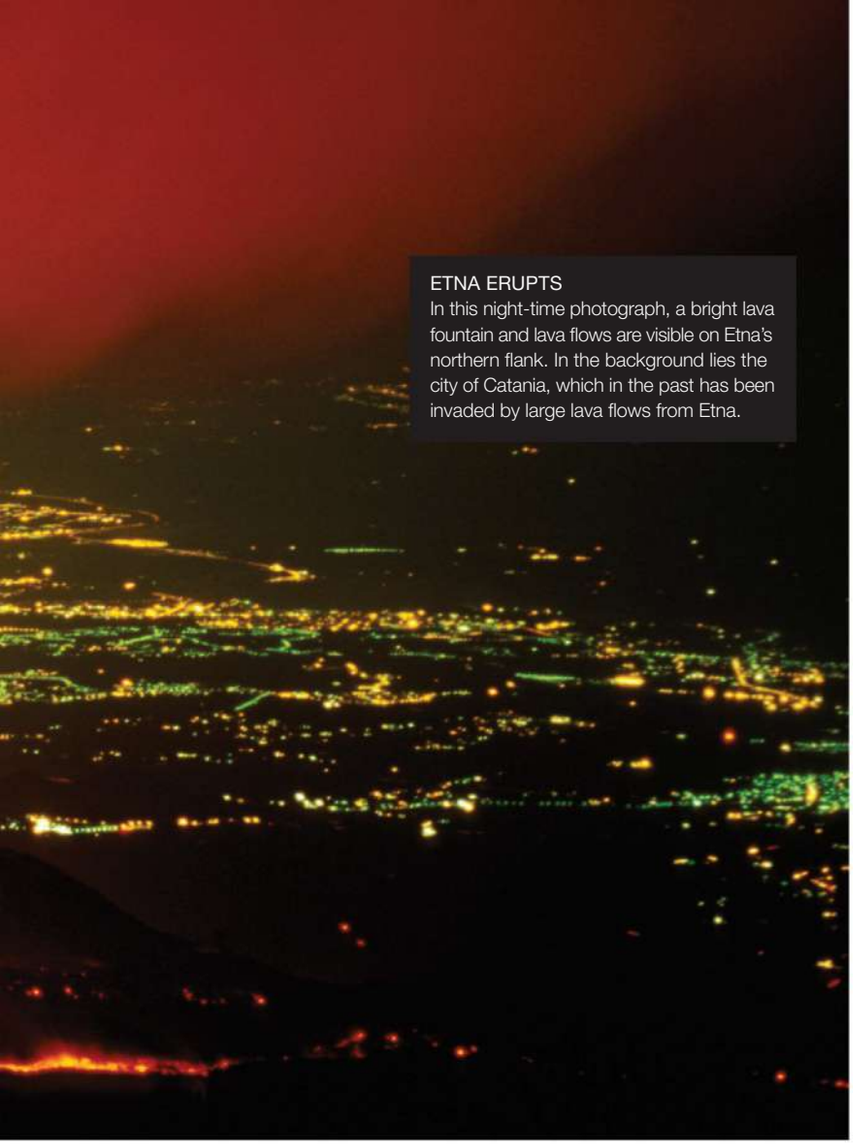
2008-09	
Location	Eastern Sicily, Italy
Volcano type	Stratovolcano
Eruption type	Hawaiian/Strombolian
Explosivity index	1–2

417

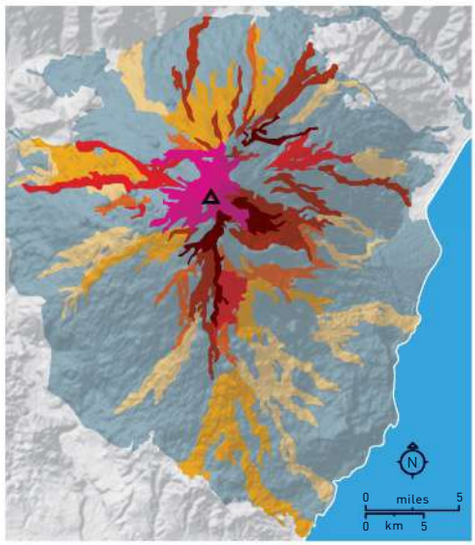
NUMBER OF DAYS THE LAVA WAS CONTINUOUSLY PRODUCED FROM THE ERUPTION VENT



SUMMIT CRATERS
Etna is unusual in having four separate summit craters, of which three are visible here. From the left, they are the Northeast Crater, La Voragine or The Chasm, and Bocca Nuova or New Mouth. These craters are 300–400m (985–1,310ft) across. In addition, there are hundreds of smaller cones and craters on Etna's slopes.



ETNA ERUPTS
In this night-time photograph, a bright lava fountain and lava flows are visible on Etna's northern flank. In the background lies the city of Catania, which in the past has been invaded by large lava flows from Etna.



LAVA FLOWS
This map shows the various times lava streams have reached the base of Etna on every side, and also beyond it.

- Summit of Mount Etna
- Historic summit lavas

Flank lava flows

- 21st century
- 20th century
- 19th century
- 18th century
- 17th century
- Pre-16th century
- Prehistoric lavas
- Pre-Etnean sediments

ERUPTION TIMELINE



1673 EXTENDED ERUPTION

An eruption that lasted from 1634 to 1638 is estimated to have produced 150 million cu m (5,300 million cu ft) of lava. This engraving of the eruption is from a book by the German scholar Athanasius Kircher, who witnessed it in 637.



1766 ETNA RESHAPED

This eruption produced an estimated 115 million cu m (4,000 million cu ft) of lava that partially reshaped Etna and threatened the town of Nicolosi on its southern flank. This depiction is by the French engraver Jean-Baptiste Chapuy.

> "...THIS TERRIBLE MOUNT UPON WHOSE CHARR'D AND QUAKING CRUST I STAND – THOU, TOO, BRIMMEST WITH LIFE!"
>
> **MATTHEW ARNOLD**, BRITISH POET, IN HIS POEM ***EMPEDOCLES ON ETNA,*** 1852

SMOKE RINGS

Etna's summit craters occasionally emit "smoke rings". These are actually rings made of steam. In February 2002, Swiss volcano-watchers witnessed a series of such rings, which are extremely rare, coming out of the volcano's Bocca Nuova crater. Some lasted for up to 10 minutes, as they slowly drifted upwards and away.



Smoking Etna
This is one of the steam rings venting from Etna's summit in February 2002. The diameter of the ring was estimated at 200m (655ft).



2002 DEVASTATION ON ALL SIDES

Lava spewed from vents on two sides of the volcano, earthquakes shook its eastern flank, while a 4-km- (2.5-mile-) high ash column rose from a crater on its southern side. Lava flows destroyed part of a forest as well as a tourist complex and skiing station.



2008 MASSIVE LAVA FLOWS

In May, a powerful eruption occurred from a fissure near Etna's summit, and several lava streams surged towards the city of Riposto. Days later, more than 200 earthquakes led to a new eruption from a flank fissure that lasted for 14 months.

MERAPI ERUPTION 2010

The eruption of Mount Merapi, a large stratovolcano on the Indonesian island of Java, in late 2010 ranks among the most serious volcanic eruptions of the 21st century. This dangerous stratovolcano (see pp. 46-47) produced a series of earthquakes, explosions, ash plumes, incandescent lava avalanches, fireballs, lahars (mudflows), and pyroclastic flows that killed more than 300 people. Several hundred million cubic metres of ash and other volcanic material were blasted over the surrounding area. Indonesia's most active volcano, Gunung Merapi (which translates as "Fire Mountain") lies in one of the world's most densely populated areas. With a height of 2,968m (9,737ft), it dominates the region immediately north of the major city of Yogyakarta. A particular problem with Merapi is that it harbours a steep-sided active lava dome at its summit that is prone to partial collapse. When a dome collapse happens, the resulting pyroclastic flows and lahars are a huge danger to people living on the slopes of the volcano, where they cultivate the fertile soil. Merapi's 2010 eruption lasted for three months, from early warning signs in September to the quietening down of the volcano in early December. The most lethal phase of the eruption, however, was from 25 October onwards.



OCTOBER-NOVEMBER 2010	
Location	Central Java, Indonesia
Type	Stratovolcano
Fatalities	353

350,000

NUMBER OF PEOPLE DISPLACED



ERUPTION
At the height of the eruption, in November 2010, an incandescent glow pervaded Merapi's summit as massive quantities of hot ash and lava surged towards the volcano's lower slopes.

THE UNFOLDING DEVASTATION



1 BEGINNING OF ERUPTION
Incandescent lava avalanches were noticed coming from the lava dome at Merapi's summit on 25 October 2010.



2 GAS AND ASH FLOWS
By 26 October, a series of pyroclastic flows were surging down Merapi's southwestern and southeastern flanks.



3 LARGE-SCALE EVACUATION
Over the next few days, with large ash plumes from the volcano rising into the atmosphere, thousands of people were evacuated.







KEEPING TRACK
A government scientist monitors activity at Merapi from the Volcano Monitoring Centre in Yogyakarta on 25 October 2010. That same day, volcanologists recommended evacuation of a region near the volcano and raised the alert to its highest possible level.

IMPACT AND CASUALTIES

Towards late October when a sharp increase in minor earthquakes near the volcano and a swelling of Merapi's lava dome was detected, villagers living within 10km (6 miles) of Merapi were advised to evacuate the area and seek refuge in emergency shelters. By 5 November, the recommended evacuation zone had been expanded to 20km (12 miles). Unfortunately, many villagers did not comply with the advice, either remaining behind or returning to their homes while eruptions continued. By the end of the eruption, the death toll had risen to 353, with most deaths due to suffocation and burns. The eruptions had blanketed a large area of forest, farms, and plantations in volcanic ash, and ash plumes from the volcano caused major disruption to air traffic across Java.

> "VOLCANIC ASH IS RAINING DOWN, IT'S DARK HERE, AND THE VISIBILITY IS ONLY TWO METRES."
>
> **BAGYO SUGITO**, A 39-YEAR-OLD DRIVER LIVING IN YOGYAKARTA



4 SEARCH AND RESCUE EFFORTS
By early November, scores of people were injured or killed as the eruption reached its most intense levels.



5 THE DESTRUCTION
Some of the worst damage was caused by lahars, which flowed for up to 16km (10 miles) and submerged villages near Yogyakarta.



6 THE AFTERMATH
Relatives in Umbulharjo village, Sleman, pray during a funeral ceremony for the victims of the eruption.



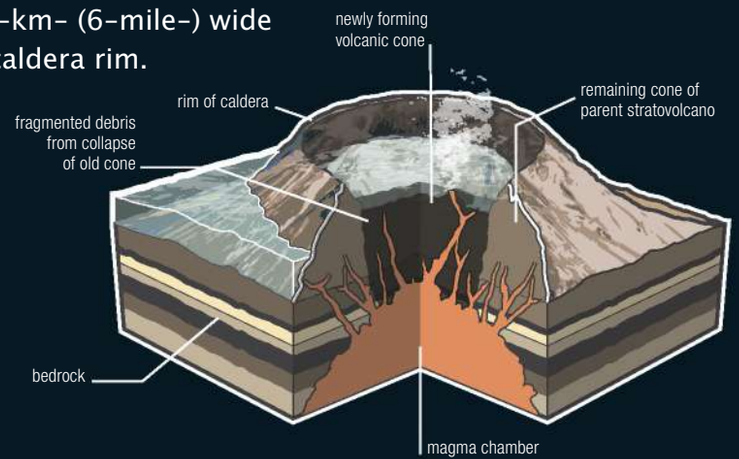
ANIAKCHAK CALDERA
This Crater-Lake type caldera is in the Aleutian Range of Alaska. Formed in a gigantic eruption 3,400 years ago, it is 10km (6 miles) across.

CALDERAS

The word "caldera" means cauldron and is a 1-km- (0.6-mile-) to 100-km- (60-mile-) wide usually circular depression caused by the eruption of vast quantities of magma. It is commonly used to refer to either of two different types of volcanic structure. One is a type of volcano in itself, the other a feature of a large stratovolcano or large shield volcano. Calderas can be gigantic – for example the Aniakchak volcano in the Aleutian Range of Alaska, USA, has a 10-km- (6-mile-) wide caldera that at its deepest is 408m (1,341ft) from the caldera rim.

TYPES OF CALDERAS

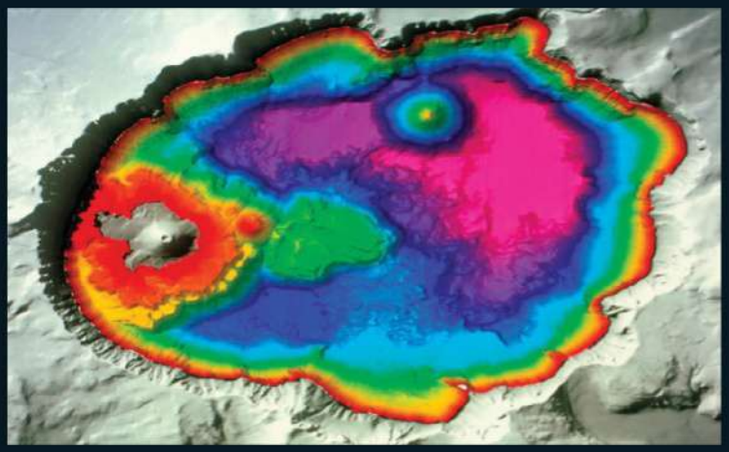
The type of landform to which the description "caldera" is most commonly applied is the remnant of a large stratovolcano (see pp.46-47) that underwent a catastrophic Plinian-style eruption and collapse, usually many thousands of years ago. These structures are volcanoes in themselves. Although there is no universally agreed name for them, they are sometimes referred to as Crater-Lake type calderas, after a caldera of this type in Oregon, USA. The second type, sometimes called subsidence calderas, result from the gradual recent subsidence of the summit of a shield volcano (see pp.40–41). Some authorities also define a third class of calderas that are too huge to have been caused by collapse of a single stratovolcano. There are only a few of these structures in the world and they are sometimes referred to as "supervolcanoes" (see pp.54–55). Each has produced some cataclysmic eruptions in the past.



CALDERA STRUCTURE
A Crater-Lake type caldera is a wide, deep crater that may contain a lake. Its floor contains debris from the collapse of a stratovolcano some time in the past.

CRATER-LAKE TYPE CALDERAS

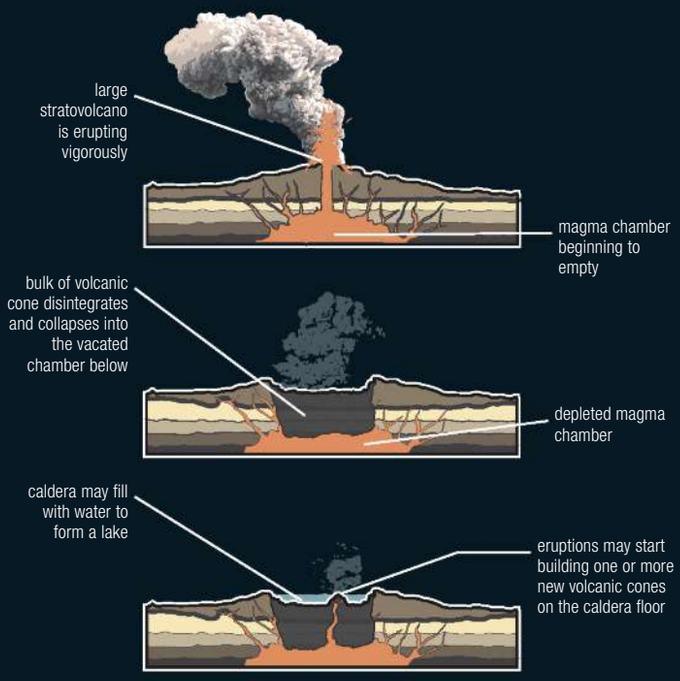
These calderas take the form of wide, often near-circular, craters, typically about 5 to 20km (3 to 12 miles) across, with rims that are usually raised hundreds of metres above the surrounding land. The archetypal example, Crater Lake itself, is filled with water to a depth of 600m (1,968ft), making it the deepest freshwater lake in North America, but not all calderas of this type contain lakes. A few Crater-Lake type calderas, such as Ngorongoro Crater in Tanzania, are definitely extinct, but many still have large chambers full of magma beneath them and may well erupt again in future. Many have new stratovolcanoes or cinder cone volcanoes growing within them.



CRATER LAKE, OREGON
Depicted here in coloured 3-D relief is Crater Lake. The depth of the crater lake floor below water level is colour coded, from red (shallowest) to purple (deepest). Crater Lake formed from the violent eruption and collapse of a gigantic stratovolcano, Mount Mazama, about 6,850 years ago.

FORMATION OF A CRATER-LAKE TYPE CALDERA

Calderas of this type usually form from the collapse of a stratovolcano. This may occur as the result of a single cataclysmic Plinian-style eruption, or in stages as the result of a series of eruptions. The total area that collapses may be hundreds of square kilometres.



SHIELD VOLCANO CALDERAS

This type of caldera is not a volcano in itself, merely the summit area of a shield volcano that has subsided over time. An example can be seen at the volcano Kilauea in Hawaii. Various collapses of its summit area have formed a roughly circular depression that is about 165m (540ft) deep and 5km (3.1 miles) across, with a floor that is a fairly flat but roughly surfaced bed of lava. Nested within it is a much smaller circular crater named Halema`uma`u. This occasionally fills with a lava lake or explosively emits gases, lava, and ash.



KILAUEA CALDERA
This view of the caldera at Kilauea's summit looks across from the caldera rim to the vertical wall on the opposite side.

THE SANTORINI CALDERA

Santorini in the southern Aegean Sea, southeast of Greece, is a series of overlapping shield volcanoes cut by at least four overlapping calderas. It has erupted many times over the past several hundred thousand years. The last major eruption, about 3,600 years ago, was one of the biggest volcanic events in recorded history. More than 60 cu km (14 cu miles) of material was blasted into the atmosphere, and a destructive tsunami was generated that may have contributed to the collapse of the Minoan civilization on the nearby island of Crete.

AN AEGEAN CALDERA
The Santorini caldera, as seen here from space, measures about 7km (4 miles) by 12km (7 miles). The island that forms about two-thirds of its rim is called Thera.



SUPERVOLCANOES

A small number of volcanoes across the world, popularly known as "supervolcanoes", have produced truly cataclysmic eruptions in the past – and are capable of future eruptions that could radically alter landscapes and severely impact the world's climate.

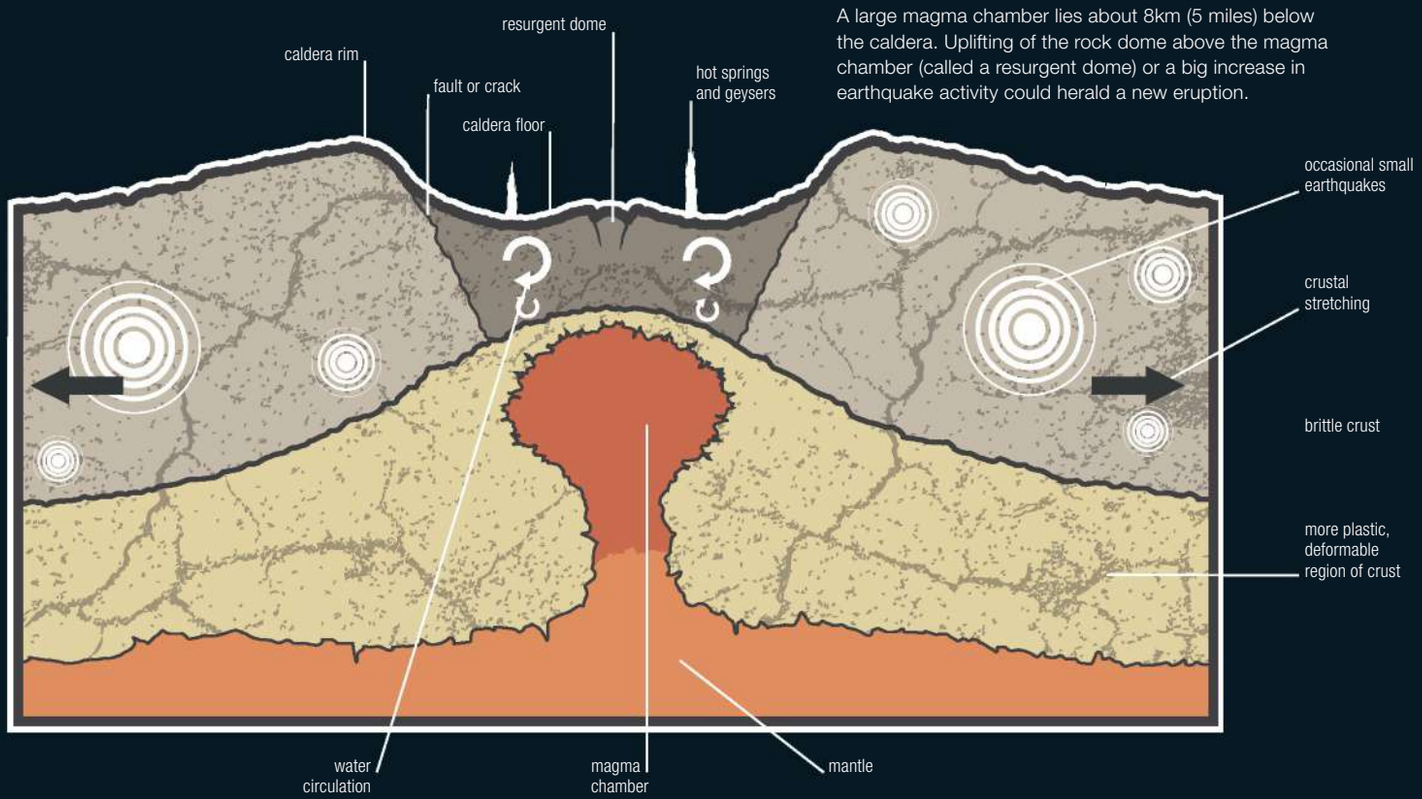
CHARACTERISTICS

A supervolcano is a volcanic site that has seen at least one eruption rating an 8 on the Volcanic Explosivity Index (see p.15) and is considered capable of future, similar eruptions. Eruptions of this size are about a thousand times bigger than anything witnessed in recent centuries, such as the 1980 Mount St Helens eruption. Only a handful of volcanic sites worldwide qualify for the supervolcano description, and all are large calderas (see pp.52–53) with underlying, active magma chambers. A prime example is Yellowstone caldera, which makes up a large part of Yellowstone Park in Wyoming, USA. Yellowstone's last big eruption, about 640,000 years ago, blasted an estimated 1,000 cu km (230 cu miles) of rock and magma into the air, and covered a large part of the western United States in volcanic ash. Further large eruptions from this caldera, with catastrophic consequences both locally and for the world's climate, are considered likely, though geologists do not believe one is at all imminent. Two other supervolcanoes are calderas underlying large, scenic lakes – Lake Taupo in New Zealand's North Island, and Lake Toba in Sumatra. The largest-known eruption at Taupo, which happened about 22,600 years ago, blasted an estimated 1,170 cu km (280 cu miles) of material into the air and caused the collapse of several hundred square kilometres of land, but the largest eruption of Toba was even bigger (see above right).



LAKE TOBA
Viewed here (in false colour) from space, Lake Toba is about 100km (62 miles) long and 35km (22 miles) wide. It nestles within an arc of volcanoes above a convergent plate boundary, where the Australian Plate is subducting beneath the Sunda Plate.

STRUCTURE OF YELLOWSTONE CALDERA
A large magma chamber lies about 8km (5 miles) below the caldera. Uplifting of the rock dome above the magma chamber (called a resurgent dome) or a big increase in earthquake activity could herald a new eruption.





DISTRIBUTION OF SUPERVOLCANOES

The three volcanic sites with the best supervolcano credentials are Yellowstone Caldera, Lake Toba, and Lake Taupo. Of these, Yellowstone sits over a continental hotspot, while Toba and Taupo are close to plate boundaries. In addition, a few other volcanic sites are close to supervolcano status, with their largest-known past eruptions scoring a 7, rather than a maximum 8, on the Volcanic Explosivity Index. These include Long Valley Caldera in California and Aira Caldera in Japan. Many other sites worldwide were once supervolcanoes but are now probably extinct.



1. Yellowstone Caldera, Wyoming
2. Lake Toba, Sumatra
3. Lake Taupo, New Zealand
4. Long Vallley, California
5. Valles Caldera, New Mexico
6. Phlegraean Fields, Italy
7. Aira Caldera, Japan
8. Kikai Caldera, Ryukyu Islands, Japan

THE TOBA ERUPTION

About 74,000 years ago, Lake Toba in Sumatra was the site of the largest volcanic eruption of the past two million years. The fact that the eruption occurred has been worked out from the thick volcanic ash deposits it left over a vast region of south Asia – it is estimated to have blasted 2,800 cu km (670 cu miles) of pulverized rock into the air. As the ash cloud travelled round the world and blocked out sunlight, it probably caused temperatures to cool by about 3–5°C (5–9°F). There is some evidence (from genetic studies) that the effects drastically reduced the world's human population at the time to about 10,000 individuals. A large magma chamber still exists under Lake Toba, and many earthquakes have occurred in its vicinity over the past century. It will probably erupt spectacularly again in the future.



BEAUTY SPOT
From its tranquil-looking setting, few would suspect Toba's catastrophic history or its potential for future cataclysm.



AIRA CALDERA, JAPAN
Some 22,000 years ago, 40 cubic km (14 cubic miles) of material was blasted out of the ground to form this caldera, a candidate for supervolcano status.



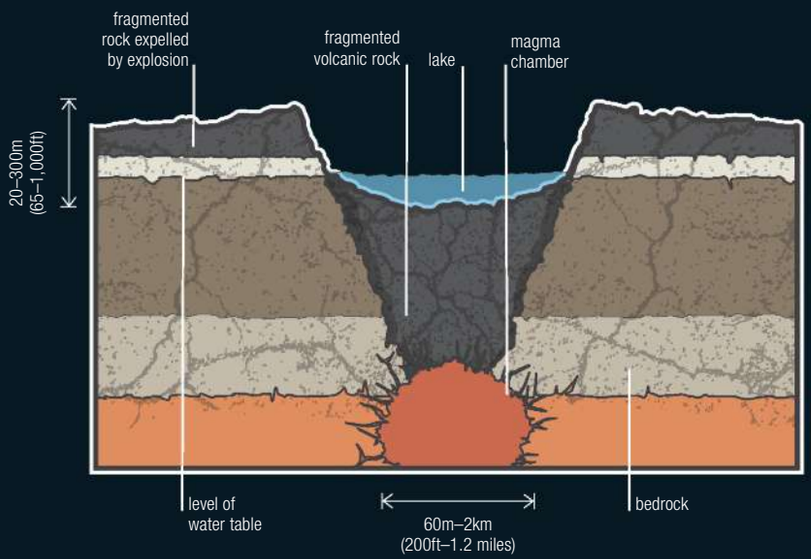
YELLOWSTONE CALDERA
Visible on the right here is the rim of the caldera, and in the middle-distance, its floor. Geologists constantly monitor the floor for any upward bulging that could indicate an imminent eruption.

MAARS

Also known as volcanic explosion craters, maars are shallow bowl-shaped volcanic craters, usually sunk slightly into the ground. These relatively small volcanic features are often filled with water to form circular lakes – the word "maar" is a German word derived originally from the Latin word "mare" (sea).

FORMATION AND SIZE

Maars are produced when magma (melted rock) reaches Earth's surface and comes into contact with groundwater or, in polar regions, ice-laden permafrost (frozen soil). The resulting steam-driven explosion excavates a shallow crater that can be anything from 60m (200ft) in diameter to considerably larger. The widest known, found on the Seward Peninsula in western Alaska, are up to 2km (1.2 miles) in diameter. They were caused by magma encountering permafrost, which results in particularly large explosions. Although there are a few dry maars in desert regions of the world, the majority are filled with lakes, which can be anything from 10 to 200m (30 to 650ft) deep.



MAAR STRUCTURE
A maar contains a mass of fragmented rock beneath it in an inverted conical structure. Below that is an extinct, or sometimes active, magma chamber. The crater is surrounded by a low rim composed of ash and loose fragments of rocks torn from the ground when the explosion happened.



DISTRIBUTION AND ACTIVITY

Maars can occur anywhere in the world where magma has come in contact with groundwater or permafrost. Some are in volcanic regions near to plate boundaries, others in locations that have experienced past or recent hotspot activity. A group of maars in the Eifel region of Germany, for example, was caused by the Eifel hotspot. Many maars are extinct, but with others, future volcanic activity is not ruled out. Two particularly dangerous maars, because of their potential for gas eruptions, are found in Cameroon and have been referred to as "exploding lakes" (see pp.58–59).

> "WE LIKEWISE FORGET, IN THESE COOL DISTRICTS OF THE EARTH, WE ARE NOT QUITE BEYOND THE HAZARD OF SUBTERRANEAN FIRES."
>
> **PUBLISHED IN THE NATIONAL MAGAZINE**, "A POSSIBLE EVENT – DANGERS OF OUR PLANET", 1854



LAC D'EN HAUT, FRANCE
This maar is part of the Chaîne-des-Puys group of extinct volcanoes in central France, created 70,000 to 7,000 years ago. Its name reflects its relatively high altitude, 1,239m (4,064ft) up in the Massif Central.

PULVERMAAR, GERMANY
Its rim completely covered by a forest, the Pulvermaar is one of several in the Eifel volcanic field, Germany. Though formed in eruptions ending 11,000 years ago, the field is regarded as still possibly active.



VITI MAAR, ICELAND
About 150m (500ft) in diameter, this Icelandic maar was formed in 1875, during an eruption of a nearby stratovolcano, Askja. Its lake waters are 35m (115ft) deep and always warm, suggesting an underlying magma chamber.



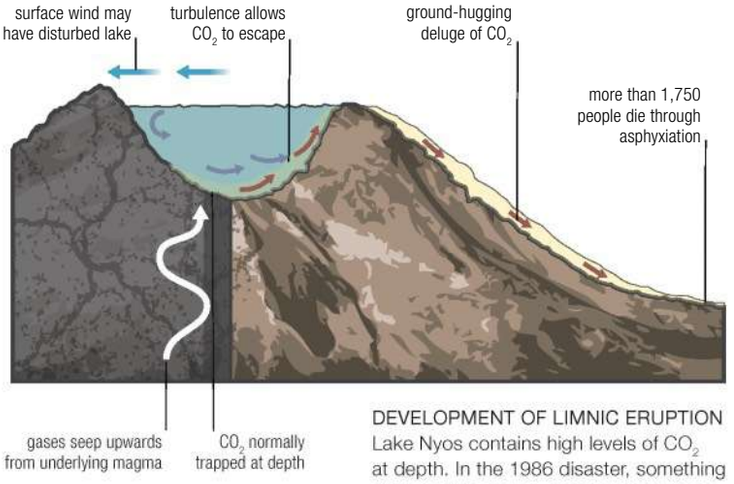
DALLOL CRATER, ETHIOPIA
This colourful maar, in the Afar Depression, formed in a 1926 eruption. Lying 45m (150ft) below sea level, the crater and others nearby are the world's lowest volcanic vents on land.

EXPLODING LAKES

In the highlands of Cameroon in west Africa are two unusual lakes, Nyos and Monoun, that sit in the craters of volcanic maars (see pp.56–57). During the 1980s, they became known as "exploding lakes" due to disasters caused by the lakes suddenly releasing large clouds of carbon dioxide.

LAKE NYOS DISASTER

The more lethal of the two disasters, known as limnic eruptions, occurred on 21 August 1986 at the larger of the two lakes, Lake Nyos. On an otherwise normal day, more than 1,750 people living in villages close to the lake suddenly died, apparently asphyxiated by something suspected to have come from the lake. Following scientific investigation, a picture of what had happened emerged. Lying in a volcanic region, Nyos has pockets of magma deep beneath it that release carbon dioxide (CO_2) and other gases. These dissolve in groundwater and feed into the lakes, so the water near the lake floor holds high concentrations of CO_2 under pressure. Eventually, when the overlying water pressure at the bottom of the lake could no longer hold the CO_2, bubbles began to form, and the low density bubble–water mixture caused the lake water to "overturn", leading to a sudden escape of CO_2 via the lake surface. At Lake Nyos, it is thought that about 1 cu km (0.25 cu miles) of the gas, which is heavier than air and tends to hug the ground, was released. It overspilt the rim of the maar and channelled down into nearby valleys, asphyxiating all people and animals in its path.



DEVELOPMENT OF LIMNIC ERUPTION
Lake Nyos contains high levels of CO_2 at depth. In the 1986 disaster, something disturbed its waters, causing the release of a vast amount of the gas.

LAKE NYOS, CAMEROON
What makes the lake particularly dangerous is its setting in a crater elevated above the surrounding land – so if a cloud of CO_2 is produced, it spills down into surrounding valleys.

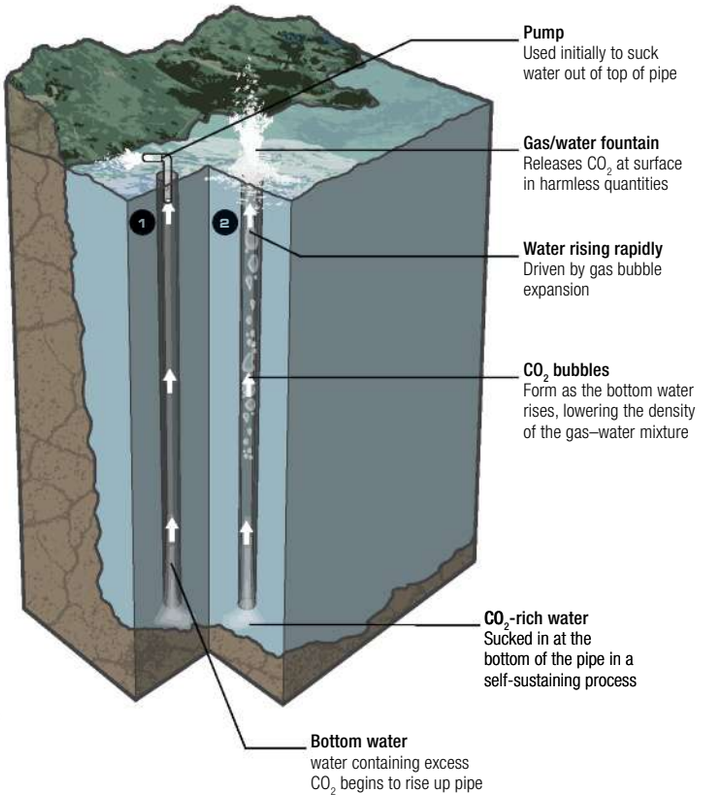
DEGASSING LAKE NYOS

The magma pocket underlying Nyos continues to recharge the lake with CO_2, so disasters are likely to recur unless excess gas is prevented from building up. In 1995, initial tests began on a degassing method. This involves setting up a strong plastic pipe vertically between the lake bottom and the surface, and initially using a pump to draw water out of and up the pipe. This triggers a self-sustaining process in which the gas-saturated bottom water is continuously sucked upwards, driven by expansion of bubbles in the rising water. At the surface, the gas is released. Degassing has been proceeding at Lake Nyos since 2001 and by the end of the decade the CO_2 levels had been greatly reduced. However, there are new concerns that an earthquake could cause partial disintegration of the Nyos maar, resulting in a disastrous flood as well as a dangerous release of the remaining gas.



EXTRACTION TECHNOLOGY
A plastic pipe is set up (1) and water pumped out at the top, causing deep water to start rising up it. The upward flow becomes self-sustaining (2) due to gas bubble formation and expansion in the rising water.

SCIENTISTS STUDY LAKE NYOS
Investigations by an international team of scientists into the geology around Nyos and its chemical make-up eventually unravelled the cause of the 1986 disaster.



Pump
Used initially to suck water out of top of pipe

Gas/water fountain
Releases CO_2 at surface in harmless quantities

Water rising rapidly
Driven by gas bubble expansion

CO_2 bubbles
Form as the bottom water rises, lowering the density of the gas–water mixture

CO_2-rich water
Sucked in at the bottom of the pipe in a self-sustaining process

Bottom water
water containing excess CO_2 begins to rise up pipe

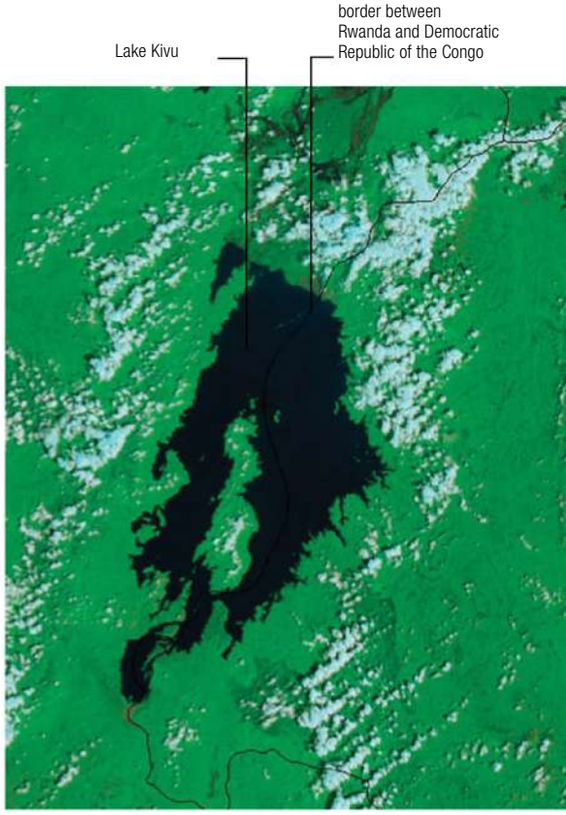


LAKE MONOUN AND LAKE KIVU

When the cause of the disaster at Lake Nyos was clarified, it was realized that a similar but smaller catastrophe, with a death toll of 37, had preceded it, at Lake Monoun in 1984. Degassing work has been in operation at Monoun since 2003, and by 2008 it was largely degassed. Scientists have also sought out other lakes that might pose similar dangers. The main one identified is Lake Kivu. This doesn't lie in a maar, but in a volcanic region within the western arm of the East African Rift Valley (see pp.100–101). There is some evidence that Kivu may have undergone large limnic eruptions in the past, and that 2 million people living close to it are in danger. As yet, no degassing system has been installed, but a scheme initiated in 2010 to extract methane from the lake has led to some degree of CO_2 degassing, too.



DEGASSING LAKE MONOUN
Japanese scientists conduct final tests from a newly assembled raft prior to the installation of one of three degassing pipes now working successfully at Lake Monoun.



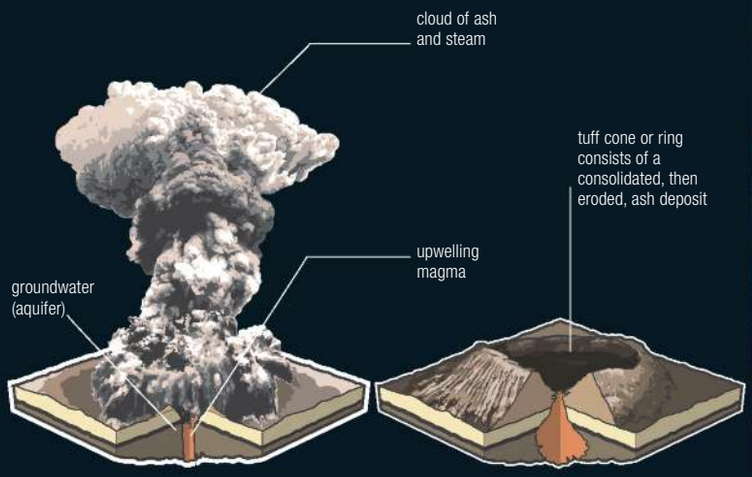
LAKE KIVU
This large lake lies in part of the East African Rift Valley – a region where Earth's crust is slowly stretching with intrusion of magma into the crust.

TUFF RINGS AND CONES

Two relatively small and simple types of volcanically created landform are tuff rings and tuff cones. Like other volcanic features called maars, they are created by violent interactions between magma (molten rock) and water. Of the two, tuff cones are more compact but have higher crater rims.

FORMATION AND STRUCTURE

Tuff rings and cones are found in areas of the world where volcanic activity is generally high (or has been in the past) – that is, near plate boundaries and hotspots – and where upwelling magma has come in contact with groundwater or surface water in the form of a lake, marsh, or shallow sea. The contact leads to a vigorous eruption with the production of ash, which falls in a ring around the eruption vent and later consolidates into a type of rock called tuff. The water involved in the creation of the cone or ring may later disappear. Tuff rings have wide, low-rimmed craters, and are often 1 to 2km (0.5 to 1 mile) in diameter. Tuff cones are smaller and more conical, with higher crater rims. Although formed in a similar way to maars (see pp.56–57), tuff rings and cones are usually not sunk into the ground or filled with water.



1 ERUPTION
Where magma contacts groundwater, a cloud of steam and ash is blown into the air. The ash rains down to form a ring or cone around the vent.

2 FORMED CONE OR RING
Over time, the ash deposit consolidates to form a ring or cone of tuff. Later, this is weathered and eroded by the action of wind and water.



DAPHNE MAJOR
This small island, one of the Galápagos Islands in the eastern Pacific, is a heavily eroded tuff cone whose rim currently rises 120m (390ft) above sea level. It is thought to have formed about 1.8 million years ago.



FORT ROCK, OREGON
This tuff ring was created tens of thousands of years ago when rising magma encountered wet mud at the bottom of an ancient lake. Once the ring had formed, waves from the lake eroded its outside walls to form terraced cliffs.



DESERT CONE
This tuff cone in the Sonoran Desert of northwest Mexico has a 1-km- (3,280-ft-) wide crater. Called Cerro Colorado, it is part of a volcanic field (group of small volcanoes).



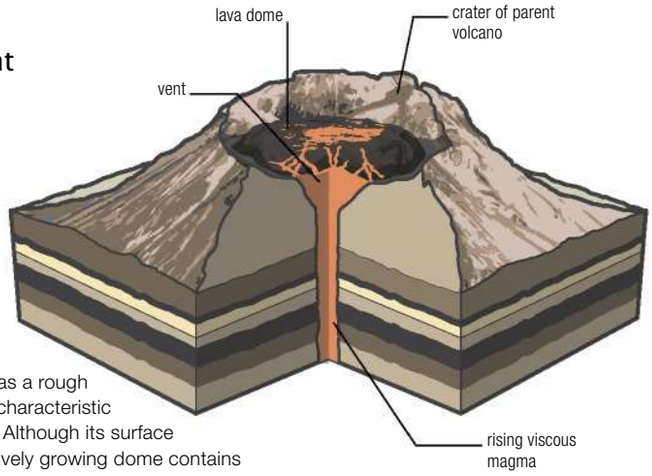
KOKO CRATER, HAWAII
This tuff cone on the island of O'ahu in Hawaii is 368m (1,207ft) high and now houses a botanical garden in its crater. No eruption has occurred here or elsewhere in O'ahu in more than 10,000 years, although future eruptions are possible.

LAVA DOMES AND SPINES

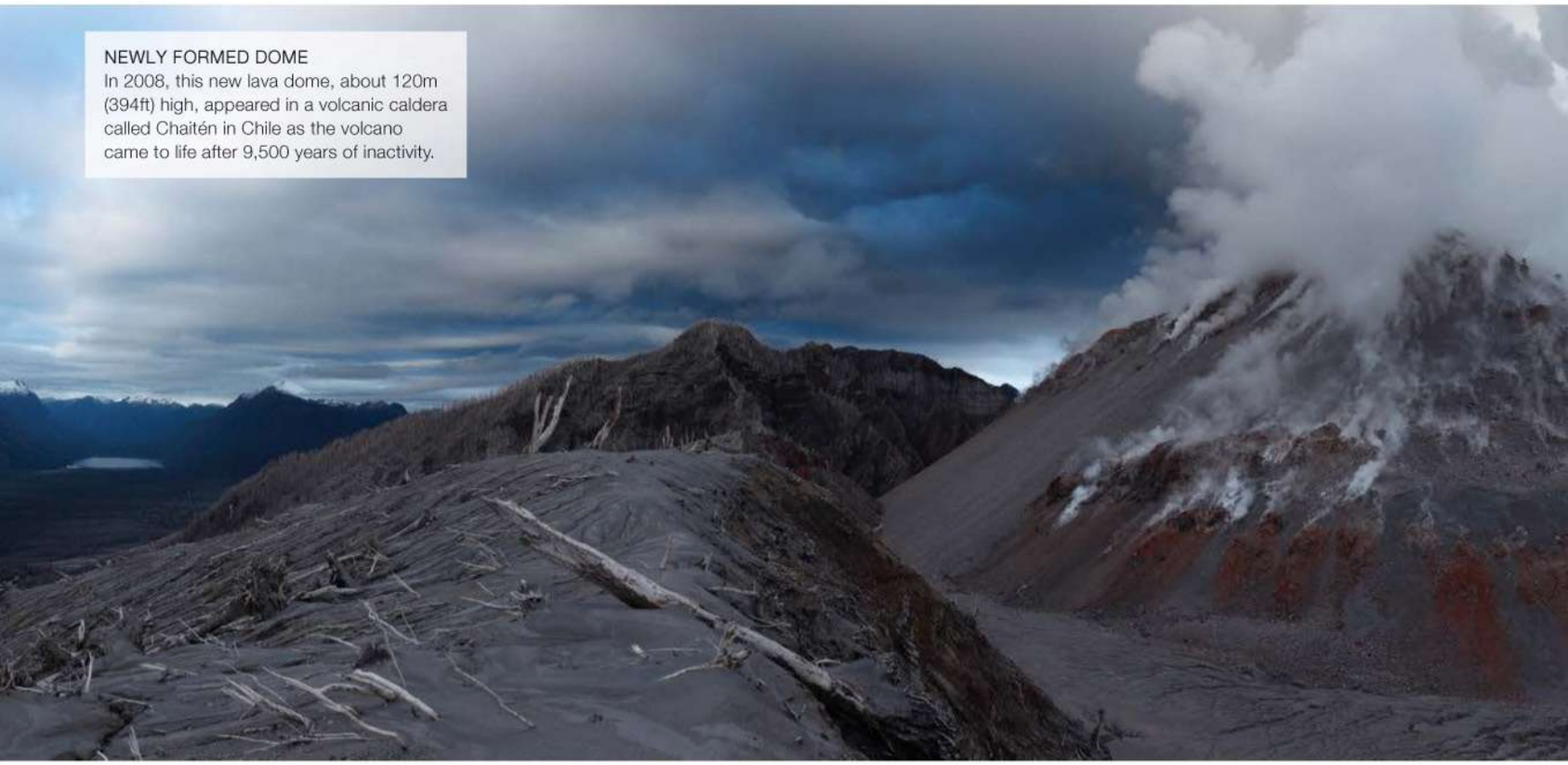
A lava dome is a craggy, bulbous, slow-growing, and potentially dangerous mass of congealed lava that develops at a volcanic vent when viscous lava oozes out. A lava spine is a bizarre-looking object that sometimes grows up vertically out of a lava dome.

DOME FORMATION

Lava domes develop at volcanic vents that extrude highly viscous lava, such as rhyolitic or dacitic lava (see p.23). Lava of this type cannot flow far from the vent from which it is being squeezed out. Instead, it piles up to form a slow-growing mound that blocks the vent. Most lava domes have developed in the main vent of a larger volcano, and sit within its summit crater, although a dome can also grow on a side vent or can even be a large separate volcano. The time it takes a dome to form and grow to its maximum size can be anything from a few weeks to several thousand years.



STRUCTURE
A lava dome has a rough surface and a characteristic mound shape. Although its surface is solid, an actively growing dome contains large amounts of hot, viscous, molten lava.



NEWLY FORMED DOME
In 2008, this new lava dome, about 120m (394ft) high, appeared in a volcanic caldera called Chaitén in Chile as the volcano came to life after 9,500 years of inactivity.

DANGEROUS DOMES

Some lava domes across the world are extinct volcanic remnants, but others are active, evolving structures undergoing processes such as growth, erosion, occasional collapse, and regrowth. As a dome enlarges, its edges creep outwards, and if one of these edges oversteepens, the dome may partially collapse to produce a dangerous landslide of hot rubble called a pyroclastic flow. Following an earthquake in 1792, the partial collapse of a lava dome on Mount Unzen in Japan created a huge landslide. This triggered a tsunami that killed about 15,000 people – Japan's worst-ever volcano-related disaster.



FIERY DOME
This glowing lava dome appeared in the middle of a crater lake during a 2007 eruption of the Kelut volcano in Indonesia. It grew to a height of 120m (394ft) before cracking open. Hot lava oozed into the lake, producing huge plumes of steam.

LAVA SPINES

These are dramatic-looking spires or fingers of solidified lava, usually cylinder shaped, that are sometimes pushed up out of lava domes on large stratovolcanoes (see pp.46–47). Lava spines are caused by highly viscous, pasty lava partially solidifying inside a volcanic vent and then being squeezed upwards – rather like hardened toothpaste emerging from a toothpaste tube. Lava spines can reach a considerable height. One that grew at the summit of Mont Pelée in Martinique (see pp.78–79), after its eruption in 1908, attained a height of 300m (984ft) and a volume comparable to that of the Great Pyramid of Giza (Egypt's largest pyramid).

Over the past 30 years, notable lava spines have developed on volcanoes such as Mount St Helens in the USA, Mount Unzen in Japan, and Mount Pinatubo in the Philippines. After growing for a few weeks or months, a lava spine becomes unstable and starts to collapse under its own weight, eventually disintegrating into a pile of rubble.



SPINE ON MOUNT ST HELENS
A series of lava spines, some of them reaching 90m (295ft) in height, grew out of a lava dome on Mount St Helens, USA, between 2004 and 2008.



FINGER-LIKE SPINE
This short-lived lava spine was pushed out of a lava dome on Mount Unzen, a group of stratovolcanoes in Japan, in 1994.





PUY DE DÔME
A large extinct lava dome in central France, Puy de Dôme (meaning dome-shaped hill) has a summit height of 841m (2,759ft). The last eruption here occurred about 10,700 years ago. In 1875 a physics laboratory was built at the summit, and in 1956 a television antenna was added.



COLIMA LAVA DOME
This dome at the summit of the Colima Volcano in Mexico has been growing for nearly a century. In early 2010, it had almost filled the volcano's summit crater. Occasionally, explosive eruptions of magma occur from the dome, causing pyroclastic flows and ash plumes.

VOLCANIC FIELDS

Volcanic fields are areas of past or present volcanic activity containing clusters of small volcanoes. From air or space, they look almost like a rash on the landscape. Like volcanoes in general, volcanic fields are usually found either on, or near, plate boundaries or above hotspots that exist, or once existed, beneath Earth's crust.

FORMATION

Volcanic fields develop where magma (molten rock) rises up beneath Earth's crust, but the channels through which the magma reaches the surface are spread over too broad an area, or the supply of magma is too little, for a single large volcano to form. Instead, many smaller volcanic features develop, although not necessarily all at the same time. Depending on the type of magma and many other factors (such as whether there is much groundwater or surface water at the eruption site), the individual volcanoes may be cinder cones (see pp.42–43), maars (pp.56–57), lava domes (pp.62–63), small stratovolcanoes (pp.46–47), or a mixture of several of these different volcano types.



PINACATE VOLCANIC FIELD
The Pinacate National Park in Mexico, seen here in a satellite photograph, contains more than 300 small volcanoes, including cinder cones, maars, tuff rings, and small lava flows.



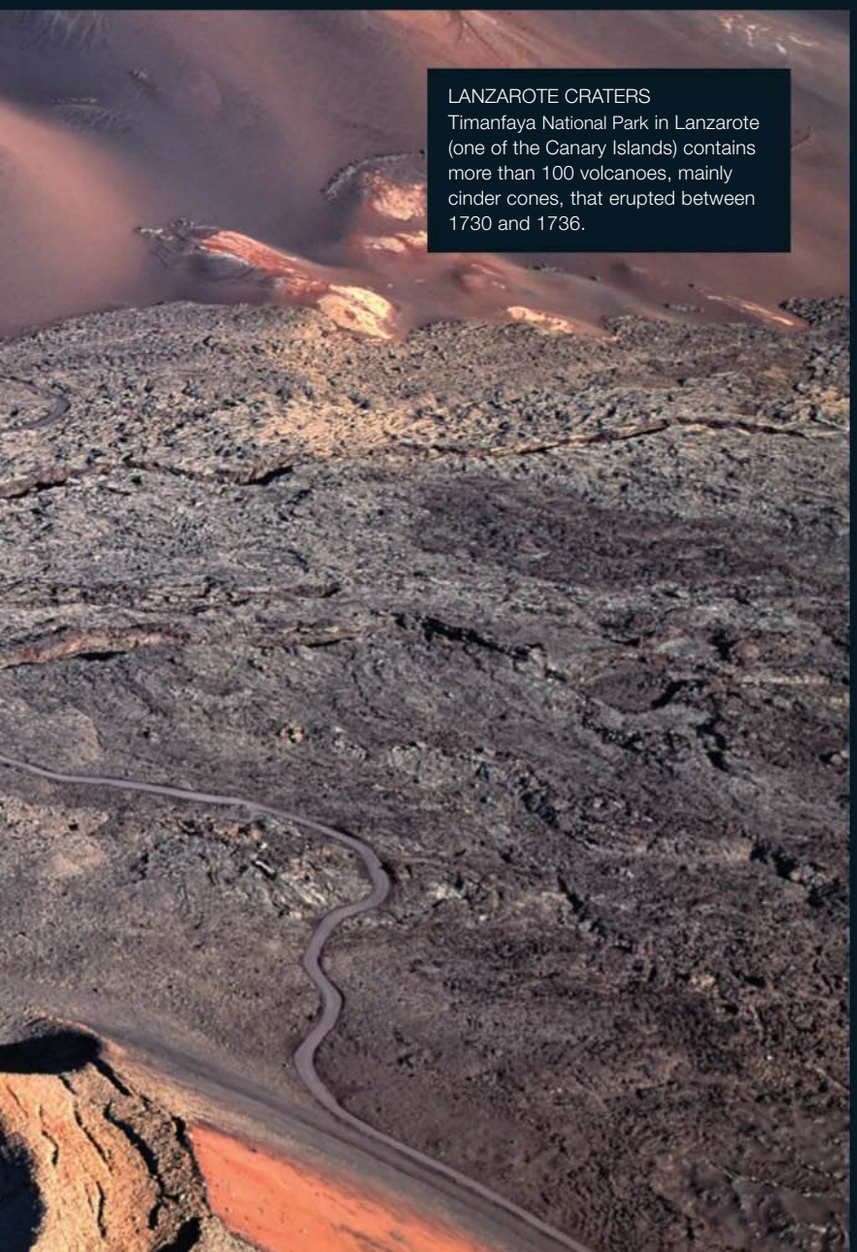
SOME NOTABLE VOLCANIC FIELDS

1. Hopi Buttes, Arizona
2. Timanfaya National Park, Lanzarote
3. Crater fields at Marsabit, Kenya
4. Chaîne des Puys, France
5. Harrat Khaybar, Saudi Arabia
6. Michoacán-Guanajuato, Mexico
7. Pinacate Biosphere Reserve, Mexico
8. West Eifel volcanic field, Germany



ACTIVITY LEVELS

In most volcanic fields, each volcano is monogenetic – that is, it only erupts once, for a relatively short period of time (anything from a few days to a few years), and then goes quiet. If a further eruption occurs later in the same region, it produces new volcanic cones and other features. Many monogenetic volcanic fields are extinct, with no further eruptions expected to happen, such as the Chaîne des Puys volcanic field in France. Others are still volcanically active, with more eruptions considered possible, such as the Timanfaya National Park in Lanzarote. In some parts of the park, the temperature of the ground just 13m (43ft) below the surface can reach as high as 600°C (1,112°F). This indicates the continuing presence of reserves of hot magma.



LANZAROTE CRATERS
Timanfaya National Park in Lanzarote (one of the Canary Islands) contains more than 100 volcanoes, mainly cinder cones, that erupted between 1730 and 1736.



HARRAT KHAYBAR
Viewed here from the International Space Station, the Harrat Khaybar volcanic field in Saudi Arabia contains a small stratovolcano as well as tuff cones and lava domes. Eruptions last occurred here about 1,400 years ago.



CHAÎNE DES PUYS
This vegetated cinder cone is one of a group of more than 70 small, extinct volcanoes in Chaîne des Puys ("chain of volcanic hills"), located in the Massif Central region of France.

ANCIENT VOLCANIC REMNANTS

The Hopi Buttes volcanic field consists of about 300 erosion-resistant volcanic remnants spread over an area of 2,500 sq km (960 sq miles) of northeastern Arizona, USA. Formed between 8 and 4 million years ago, its most prominent features are scattered dark volcanic plugs. These are mixed in with numerous maars (shallow craters formed by explosive interactions between magma and groundwater).



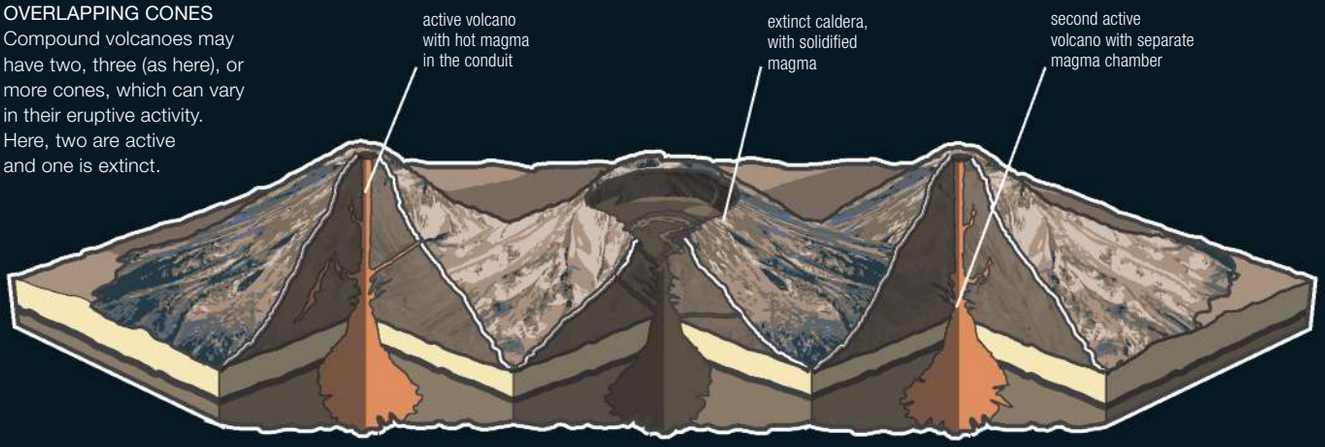
Dark volcanic plugs
These mounds were originally hardened plugs of lava or cemented fragments of volcanic rock that formed below the land surface. They were exposed by erosion of the surrounding softer rock.

VOLCANIC COMPLEXES

Although many volcanoes have a simple form, with a single main vent and crater at the top of a single cone, others have more complicated structures. They include volcanoes with overlapping cones and multiple craters, and some where new cones develop within the remains of older stratovolcanoes.

COMPOUND VOLCANOES

Sometimes called complex volcanoes, these structures consist of two or more volcanoes, usually stratovolcanoes (see pp.46–47) that have formed close to each other, with separate main conduits and vents, and partially overlapping cones. They can form as a result of small shifts in the spot where rising magma reaches Earth's surface. Usually, the separate cones have formed at different times. Compound volcanoes typically have multiple summit craters. One of the strangest is Kelimutu, on the island of Flores in Indonesia. This has three summit craters, each containing a different coloured lake.



OVERLAPPING CONES
Compound volcanoes may have two, three (as here), or more cones, which can vary in their eruptive activity. Here, two are active and one is extinct.

SOMMA VOLCANOES

A somma volcano consists of one or more stratovolcanoes that have grown to occupy a large part of the caldera that survives from an older, collapsed stratovolcano. The best-known somma volcano in the world is the Vesuvius/Somma volcanic complex in southern Italy (see pp.82–83). This consists of a stratovolcano, Vesuvius, that has grown up within the caldera of a larger, more ancient volcano, called Monte Somma – hence the name for this type of volcanic complex. Somma volcanoes are not common. Most identified examples are in the remote Kuril Islands of the northwestern Pacific or in the Kamchatka Peninsula of eastern Russia. Another classic example is the Teide/Pico Viejo/Las Cañadas complex on Tenerife in the Canary Islands. In this somma volcano, two stratovolcanoes, Teide and Pico Viejo, have developed over the past 150,000 years within the ancient Las Cañadas caldera, which originally formed at least 3.5 million years ago.



TEIDE, TENERIFE
In this view of the island of Tenerife based on satellite imagery, the Teide and Pico Viejo volcanoes sit at the centre, within the surrounding steep walls of the roughly elliptical Las Cañadas caldera. Tenerife is an entirely volcanic island – the third largest in the world by volume.

CALDERA COMPLEXES

Caldera complexes consist of one or more large volcanic calderas that contain several additional, more recently formed volcanic features growing within them. Where there is more than one caldera, they may overlap, and the newer volcanoes – which may be stratovolcanoes, cinder cones (see p42–43), or lava domes (see pp.62–63) – may be coalesced together, as for example in the Taal caldera in the Philippines. One of the largest caldera complexes in the world is the Masaya caldera complex in Nicaragua. This consists of several partially overlapping pit-like craters at the summit of twin volcanic cones, which lie within the Masaya caldera.



CINDER CONE IN TAAL CALDERA
This cone is part of the Taal caldera complex, a group of volcanoes within a large, lake-filled caldera. The cone is joined with others to form a volcanic island called Volcano Island, the site of many eruptions.





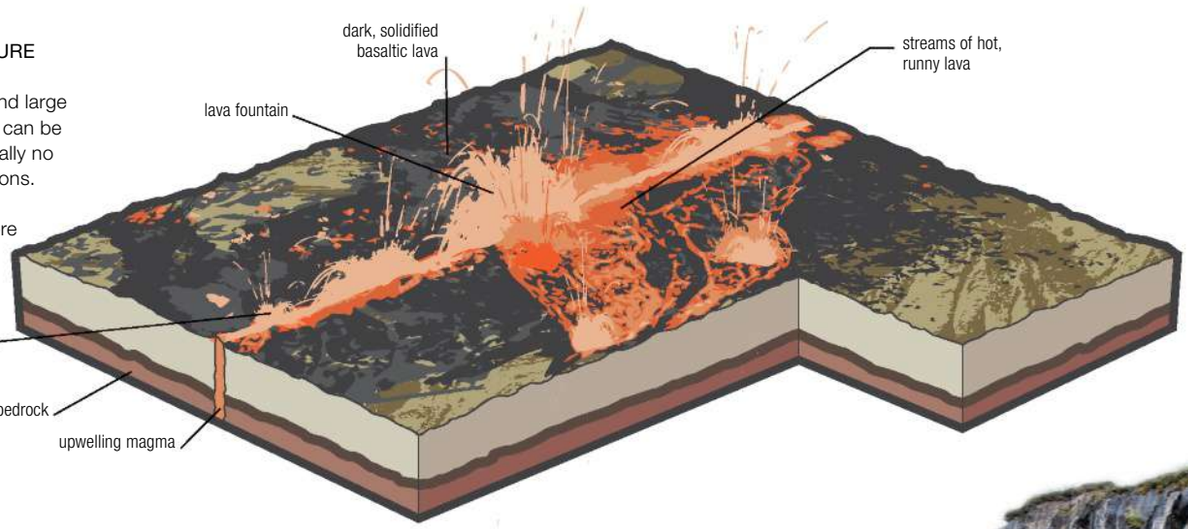
TENGGER COMPLEX
This large volcanic complex in Java, Indonesia, consists of five stratovolcanoes within an older caldera. On the edge of the complex, and seen in the background here, is an active stratovolcano, Semeru.

FISSURE ERUPTIONS

Fissure or Icelandic-type eruptions are voluminous outpourings of lava and poisonous gases from long linear cracks, called fissure vents, that appear in the ground. These eruptions usually occur fairly quietly, without loud explosions, but their effects can be dramatic – in the past they may have caused climate change and mass extinctions.

PRODUCTION OF FLOOD BASALTS

Fissure eruptions occur mainly in parts of the world where Earth's crust is rifting or being stretched, usually at a divergent plate boundary, or where the crust lies over a mantle plume at a hotspot. The lava that emerges is usually runny basaltic lava, which flows a considerable distance – up to tens of kilometres – before it solidifies. At various times over the past 300 million years, fissure eruptions have built up extensive thick deposits or plateaus of hardened basaltic lava in various parts of the world. The largest of these flood basalts, as they are called, are the Siberian Traps, which formed 250 million years ago and cover 2 million sq km (0.77 million sq miles) of northern Russia. Other flood basalts include the 2,000-m- (6,562-ft-) thick Deccan Traps of west-central India (formed 68–60 million years ago), the Columbia River Basalt Group of the northwestern USA (formed about 15 million years ago), the Chilcotin Plateau Basalts in British Columbia, Canada, and the Antrim Plateau of Northern Ireland.



ERUPTION FROM A FISSURE
Many small lava fountains appear along the fissure, and large amounts of poisonous gas can be given off, but there are usually no large ash clouds or explosions. The molten lava can flow a considerable distance before it solidifies to form basalt.



RATHLIN ISLAND
This small island off the coast of Antrim, Northern Ireland, is part of a group of flood basalts created 60–50 million years ago during a rifting process that led to the opening of the North Atlantic.



CHILCOTIN BASALTS
Over the past 10 million years, fissure eruptions created vast flood basalts in British Columbia, forming the Chilcotin Plateau. This canyon was formed by a river eroding the plateau.



SVARTIFOSS WATERFALL
This waterfall in Iceland is famous for the dark hexagonal basalt columns that hang off the cliffs like organ pipes at each side. These formed as lava cooled 15 million years ago.

THE LAKI ERUPTION

An eruption that occurred in 1783–84 from a fissure called Laki in Iceland is reckoned to be the most deadly volcanic catastrophe in recent history, causing more than six million human deaths worldwide. Clouds of poisonous gases from the fissure killed more than half of Iceland's livestock, leading to a famine in which a quarter of the country's human population died. A haze of dust and gas spread over northern Europe, then more widely across the northern hemisphere, causing many deaths directly from respiratory illnesses, but also a drop in temperatures, crop failures, and famines. The disruption to agriculture in France, and the resulting poverty and famine, is credited with triggering the French revolution in 1789.



THE LAKI FISSURE
This line of volcanic cones in southern Iceland marks the fissure from which the Lakagigar, or Laki, lava flow erupted in 1783–84. Over an eight-month period, an estimated 14 cu km (3 cu miles) of lava poured out over the surrounding terrain.

> "THE PECULIAR HAZE OR SMOKY FOG THAT PREVAILED IN THIS ISLAND, AND EVEN BEYOND ITS LIMITS, WAS A MOST EXTRAORDINARY APPEARANCE."
>
> **GILBERT WHITE**, NATURALIST, DESCRIBING THE EFFECT OF THE LAKI ERUPTIONS ON BRITAIN

FIMMVÖRÐUHÁLS ERUPTION
This lava flow is from a 300-m- (984-ft-) long fissure that appeared in Fimmvörðuháls in southern Iceland in March 2010. The fissure eruption was merely a prelude to the Eyjafjallajökull eruption in April.

HAWAIIAN-STYLE ERUPTIONS

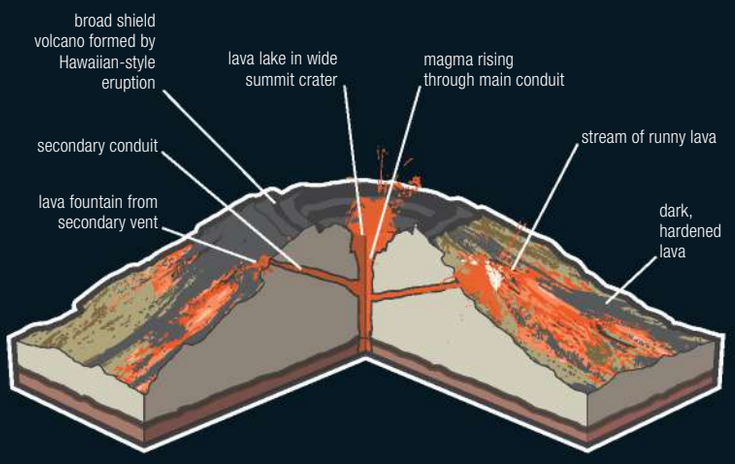
Hawaiian-type volcanic eruptions are typically mild events characterized by the emission of fountains and streams of runny lava. Eruptions of this type occur in many parts of the world, not just Hawaii. Larger more explosive eruptions can occur from these volcanoes – in recent history the three active volcanoes on Hawaii's Big Island have mainly erupted this way.

CHARACTERISTICS

Hawaiian-style eruptions occur when there is basaltic (runny) magma that contains little dissolved water and gas. These conditions are common when the magma comes from a hotspot or mantle plume under Earth's crust rather than from a convergent plate boundary. Hawaiian-style eruptions build up broad shield volcanoes, such as Mauna Loa and Kilauea in Hawaii. Before an Hawaiian-style eruption, the volcano may swell or inflate a little. Next there may be an escape of gas. Actual eruptions typically start with a fissure opening on a flank of the volcano and lava spurting out in small fountains. This may progress to the appearance of larger fountains from secondary cones. The hot lava moves downslope in streams. Lava tubes may form on the flanks of the volcano and facilitate the flow of molten lava for many kilometres.



HAWAIIAN ISLAND CHAIN
This satellite image shows six of Hawaii's volcanic islands. The most prominent volcano on the Big Island, at bottom right, is Mauna Loa.



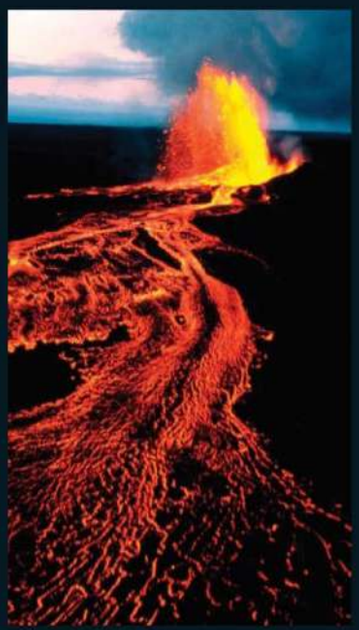
ERUPTION FEATURES
In Hawaiian-style eruptions there is a steady fountaining of lava from fissures and small cones on the flanks of the volcano. Less commonly, lava overflows or is sprayed up in a jet from the volcano's central crater.

MAUNA LOA ERUPTION
Hot lava bubbles up and flows away from a large vent on the Hawaiian shield volcano Mauna Loa in 1984. During that eruption, the volcano produced about 220 million cubic meters (0.5 million cubic miles) of lava in just three weeks.

DEVELOPMENT OF AN ERUPTION



1 LAVA FOUNTAIN
Voluminous fountains and jets of lava, as here from the Pu'u 'O'o vent on Kilauea, are a hallmark of Hawaiian-style eruptions. The fountains and jets usually develop soon after the eruption starts. They can occur in short spurts or last for hours on end.



2 WIDE LAVA STREAM
Some lava flows away from the eruptive vent in wide streams. These normally consist of the hottest, thinnest type of basaltic lava, called pahoehoe. It can travel for long distances even over the shallow slopes typical of shield volcanoes.



3 LAVA TUBE
Thick flows of lava sometimes develop into channels enclosed by solidified lava. A space can form in the roof of one of these lava tubes – a skylight – allowing observers to look down at the lava flow. Lava tubes can be up to 15m (50ft) below the surface.

POTENTIAL HAZARDS

The runniness of the lava and lack of gas in the type of magma associated with Hawaiian-type eruptions means that few explosions, large volcanic bombs, or pyroclastic flows are produced. They are normally relatively safe to witness. In Hawaii, only a handful of fatalities have occurred directly as a result of eruptions on Mauna Loa and Kilauea in recent years, although many houses have been destroyed.



ENTERING THE SEA
Lava on Hawaiian and other island-based volcanoes sometimes cascades right down to the sea, producing large plumes of steam when it enters the water.





BURSTING MAGMA BUBBLE
A bubble of red-hot magma explodes from a vent on Kilauea shield volcano on the Big Island of Hawaii. Stringy globs of magma can be seen being blown sideways from the vent by the erupted gases. These are spun out by the wind into long, glassy fibres called Pele's hair.



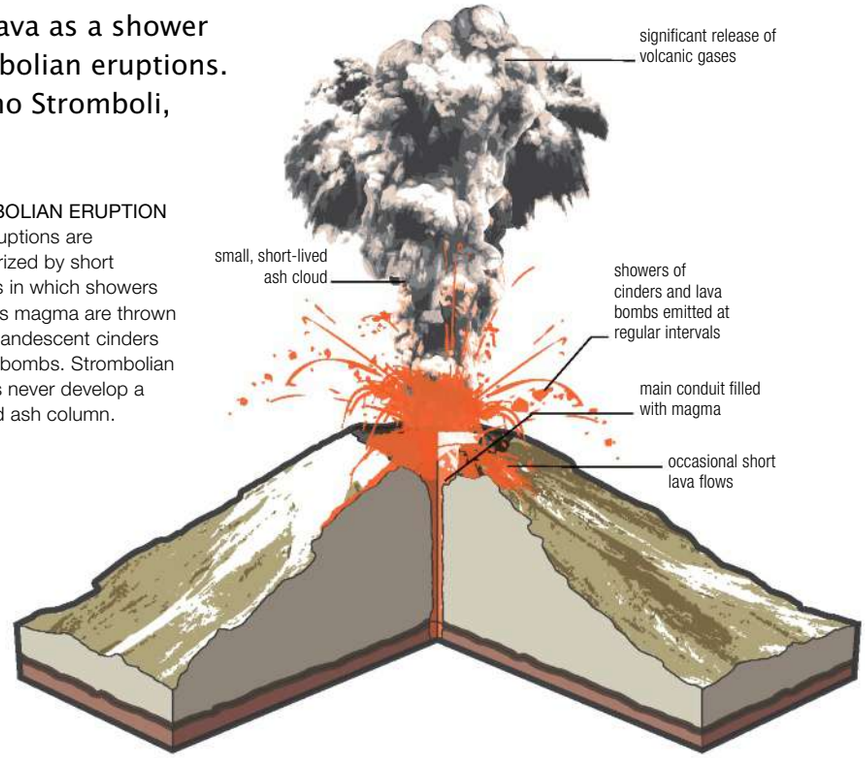
SPRAY OF BOMBS
This long-exposure photograph of a night-time eruption from Stromboli shows the paths of the small volcanic bombs ejected from the crater. Each falls to the ground in a parabolic arc. Also visible is some erupted steam, which glows red by reflecting light from the incandescent lava.

STROMBOLIAN ERUPTIONS

Low-intensity, episodic eruptions that emit lava as a shower of little "bombs" into the air are called Strombolian eruptions. These are named after the small stratovolcano Stromboli, off the north coast of Sicily.

CHARACTERISTICS

Strombolian eruptions are commonly produced by cinder cone volcanoes (see pp.42–43) and from certain stratovolcanoes (see pp.46–47), notably Stromboli itself, which has been called the "Lighthouse of the Mediterranean". Eruptions occur as a series of short, explosive outbursts that throw showers of lava fragments into the air. Each outburst can be accompanied by noisy bangs but no really large explosions. Some scientists think that Strombolian eruptions are caused by bubbles of gas rising up through the viscous magma in the volcano's conduit and bursting explosively at the top. They may be caused by cyclical gas pressure variations in the volcano's vent. Strombolian eruptive activity can be long-lasting because the eruptive system resets itself.



STROMBOLIAN ERUPTION
These eruptions are characterized by short outbursts in which showers of viscous magma are thrown up as incandescent cinders and lava bombs. Strombolian eruptions never develop a sustained ash column.

POTENTIAL HAZARDS

Although Strombolian eruptions are much noisier than Hawaiian-style eruptions (see pp.70–71), they are not much more dangerous. Nevertheless, onlookers need to stand well back from the area where volcanic bombs are falling. Although these bombs are usually not large, some of them fall from a height of several hundred metres, so have acquired a considerable speed and potential to injure by the time they reach the ground. Unlike in Hawaiian-style eruptions, there are rarely any sustained lava flows over the ground in Strombolian eruptions, lessening the potential risk. Stromboli itself occasionally erupts in a more violent and dangerous Vulcanian-style eruption see pp.76–77) and has killed people doing so. An eruption in 1930, for example, produced lava bombs that destroyed several houses and a pyroclastic flow that killed four people.



MOUNT YASUR, VANUATU
This volcano on Tanna Island, Vanuatu, in the southwestern Pacific, has been producing Strombolian eruptions for centuries. Its glowing summit attracted Captain Cook to Tanna in 1774.



TWISTED BOMB
Most lava bombs emitted in Strombolian eruptions are no more than 20cm (8in) in diameter.



STROMBOLI BY DAY
Some 900m (2,950ft) high, Stromboli has been erupting every 5 to 20 minutes for thousands of years. This makes it a significant tourist attraction in the central Mediterranean region.

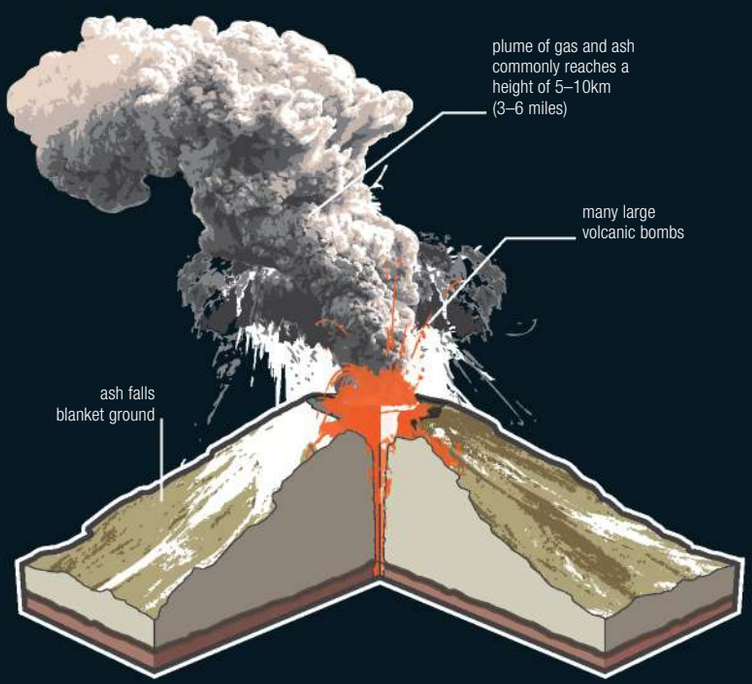
VULCANIAN ERUPTIONS

Vulcanian eruptions are moderately violent volcanic events that always start with cannon-like explosions. They are named after the small volcanic island of Vulcano in the Mediterranean, which had a Vulcanian-type eruption in 1890 and also contributed the word "volcano" to most European languages.

CHARACTERISTICS

Vulcanian eruptions usually rate at either level 2 or level 3 – described as explosive to severe – on the Volcanic Explosivity Index (see p.15). Only stratovolcanoes (see pp.46–47) that produce medium- to high-viscosity lava erupt in this way. The explosions that invariably herald a Vulcanian eruption occur as mounting pressure causes a lava plug in the volcano's vent to be blown away. Following the initial volley of explosions and with the production of an ash column, further large bangs occur, at intervals ranging from a few minutes to as much as a day. Also produced are many large volcanic bombs – these are commonly found on the ground after an eruption as "breadcrust" bombs, so-called because their cracked surfaces are reminiscent of the crust of some types of bread loaf.

In most cases, Vulcanian eruptions quieten down within a few hours to days, sometimes ending with a flow of viscous lava. In other cases, activity may continue for years, with occasional explosive eruptions alternating with longer periods of quiet steam emission.



ERUPTION FEATURES

With each explosion, a dense cloud of ash-laden gas is blasted from the volcano's crater and rises high above the peak, the ash forming a fairly large eruptive column before drifting to the ground over a wide area. In addition, there are many high-velocity ejections of large volcanic bombs.

POTENTIAL HAZARDS

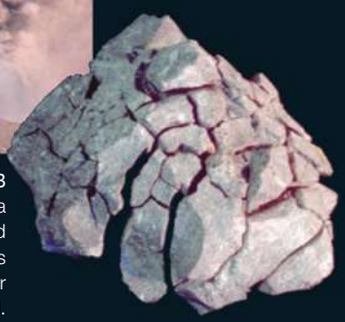
Vulcanian eruptions are extremely dangerous for anyone within several hundred metres of the eruption vent because of the volcanic bombs they produce, which can be as much as 2 to 3m (7 to 10ft) in diameter. Despite their name, volcanic bombs rarely, if ever, explode. Nevertheless they can cause severe damage on impact, and because they are often still red-hot or even incandescent when they fall, can set buildings and vegetation on fire. Volcanoes that produce Vulcanian eruptions also commonly harbour growing lava domes (see pp.62–63), which if they disintegrate, can result in dangerous pyroclastic flows down the sides of the volcano. For these reasons, anyone studying or witnessing a Vulcanian-style eruption is advised to remain several kilometres away from its volcanic vent. For example, anyone visiting Anak Krakatau in Indonesia during one of its eruptive phases is kept at a distance of 3km (2 miles) from the active cone and prohibited from landing on Anak Krakatau island itself.



ANAK KRAKATAU
This volcano in Indonesia has been producing spectacular Vulcanian-style eruptions since 2007. It grew from part of the remains of the volcanic island of Krakatau, which exploded dramatically in 1883.



IRAZÚ
This large ash cloud was emitted by Costa Rica's highest volcano, Irazú, during a Vulcanian eruption in 1963. A great quantity of ash later showered down on the Costa Rican capital of San José, 24km (15 miles) away.



BREADCRUST BOMB
The cracked surface of a bomb of this type is caused by the expansion of gas within its still-liquid interior after it has hit the ground.

KILLER COLOMBIAN VOLCANO

The volcano Galeras in Colombia has produced many Vulcanian eruptions over the past 40 years. A sudden eruption in 1993 produced volcanic bombs and poisonous gases that killed nine people, including six scientists. Aside from that incident, Galeras is considered highly dangerous because it lies just 8km (5 miles) from the city of Pasto with a population of 450,000.



Radar image of Galeras
In this satellite radar image, Galeras is the green area at centre, while Pasto is the orange area at bottom right.

PELÉAN ERUPTIONS

In some volcanic eruptions, the key event is an avalanche of hot gas, rock, and ash caused by the collapse of a dome, which feeds a pyroclastic flow that sweeps downhill. These eruptions are named Peléan, after a notorious example that occurred at Mont Pelée, Martinique, in 1902.

CHARACTERISTICS

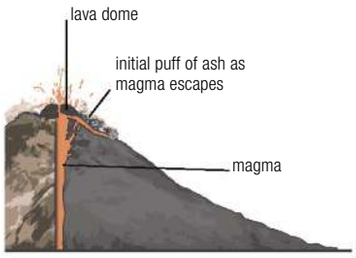
Peléan eruptions are among the most dangerous and destructive of all volcanic eruptions. They usually rate at 3 to 4 on the Volcanic Explosivity Index (see p15). Most of the damage is caused by pyroclastic flows of hot gas, rock, and ash down the sides of the volcano – which may generate even more dangerous pyroclastic surges. Surges contain higher levels of gas than flows and can travel at higher speeds. Only stratovolcanoes that produce high-viscosity lava erupt in this way. Typically, a Peléan eruption is preceded by the development of a lava dome at the volcano's summit. If this collapses, magma may be blasted out sideways, producing a pyroclastic flow, which incinerates all in its path. A new lava dome usually then develops at the summit creating the likelihood of another collapse and pyroclastic flow.

DEVELOPMENT OF A PELÉAN ERUPTION

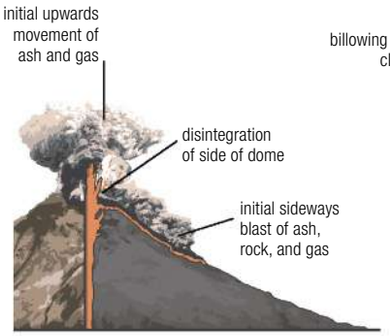
An eruption of this type is typically triggered when rising pressure within the volcano, or an event such as an earthquake, causes partial disintegration of a lava dome at its summit.

PYROCLASTIC FLOW ON UNZEN

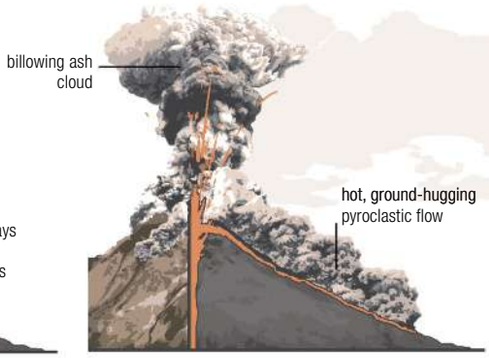
A small pyroclastic flow is seen moving down Mount Unzen in Japan in May 1993. The volcano underwent some violent Peléan-like eruptions between 1991 and 1994.



1 PARTIAL COLLAPSE
Pressure begins to force gas and magma out from beneath a collapsing lava dome. The magma erupts as ash.



2 ERUPTION
Suddenly, as part of the dome disintegrates, large amounts of magma, gas, and rock fragments are blasted out.



3 ASH CLOUD SURGE
The ash cloud can billow to a height of 5 to 10km (3 to 6 miles), while a pyroclastic flow rushes to the foot of the volcano.



RECENT PELÉAN ERUPTIONS

1. Pelée, Martinique 1902
2. Hibok-Hibok, Philippines 1948–51
3. Lamington, New Guinea 1951
4. Bezymianny, Kamchatka 1956, 1985
5. Mayon, Philippines 1968, 1984
6. Soufrière Hills, Montserrat 1995–99
7. Unzen, Japan 1991–95



Mount Mayon, Philippines



Soufrière Hills, Montserrat

THE MONT PELÉE DISASTER

The most lethal volcanic eruption of the 20th century, and one of the five deadliest of all time, occurred from the stratovolcano Mont Pelée, on the Caribbean island of Martinique, on 8 May 1902. It involved a pyroclastic flow that moved at a speed of more than 600kph (370mph). This, in turn, generated a pyroclastic surge that quickly overwhelmed the port city of St Pierre, about 6.5km (4 miles) from Mont Pelée's summit, killing almost its entire population of about 30,000. There were only three survivors in the direct path of the flow, one of whom was in an enclosed dungeon-like jail cell. A French volcanologist, Alfred Lacroix, who visited Martinique shortly afterwards, described these events as *nuée ardentes* ("glowing clouds"). In 1929, another eruption occurred from Mont Pelée, and further eruptions are expected in future, although the mountain is now closely monitored by volcanologists.



MAP OF MARTINIQUE
On this map, made soon after the disaster, the various deposits of lava and pyroclastic material (ash and rock fragments) from Pelée are shown in red. St Pierre is shown in a small bay at the base of the volcano's southern flank.



PYROCLASTIC SURGE
This photograph, taken in December 1902, shows a pyroclastic surge from Pelée similar to the one that tragically engulfed St Pierre in May 1902. It was one of several flows and surges that occurred in the months after the original disaster.





> "I SAW ST PIERRE DESTROYED. THE CITY WAS BLOTTED OUT BY ONE GREAT FLASH OF FIRE."
>
> AN ASSISTANT PURSER ON THE SS *RORAIMA*, WHICH REMAINED TEMPORARILY AFLOAT, ALTHOUGH AFLAME, IN THE HARBOUR OF ST PIERRE

RUINS OF ST PIERRE
The city burned for several days after the disaster and nearly every building was destroyed. Today the population of St Pierre is just over 4,500, and although the city was never restored to its former glory, many structures are built upon the foundations of pre-eruption buildings.

PLINIAN ERUPTIONS

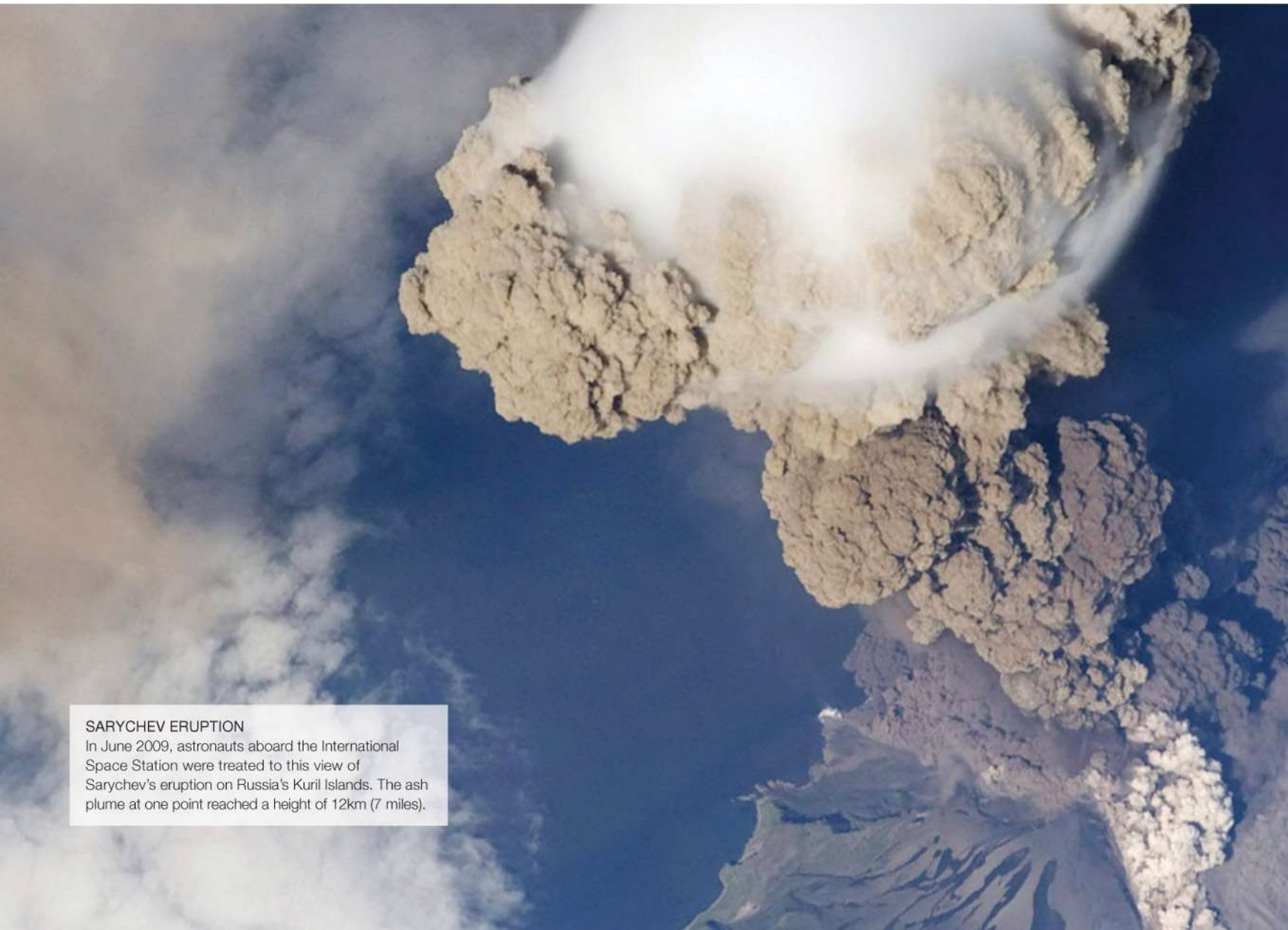
The most explosive and violent of all volcanic events are Plinian and ultraplinian eruptions. These eruptions blast a steady, powerful stream of gas and fragmented magma into the air, producing a gas and ash cloud that typically takes the shape of a huge mushroom or cauliflower.

OCCURRENCE

Also called Vesuvian eruptions for their similarity to the deadly eruption of Mount Vesuvius in 79CE, Plinian eruptions are named after the Roman author Pliny the Elder, who died during the event, and his nephew, Pliny the Younger, who observed and later described it in a letter. These eruptions usually stand between 4 and 6 on the Volcanic Explosivity Index, or VEI (see p.15). Those above 6 are called ultraplinian. They only occur in stratovolcanoes or caldera systems that produce very viscous lava, usually rhyolitic (see pp.22–23). Only a few stratovolcanoes have consistently produced such eruptions. These include Vesuvius, which has erupted in a similar fashion about a dozen times since 79CE, and Mount St Helens, with four or five Plinian eruptions over the past 600 years. Usually, the erupting volcano has shown no activity for hundreds or thousands of years. Chaitén, in Chile, which erupted in 2008, had not seen any volcanic activity in the previous 7,000 years. This indicates that to produce such eruptions, huge amounts of magma and pressure have to build up over time within or under the volcano. In some Plinian eruptions, the amount of magma erupted is so large that the top of the volcano collapses, resulting in a caldera (see pp.52-53).

PLINIAN ERUPTIONS IN HISTORY

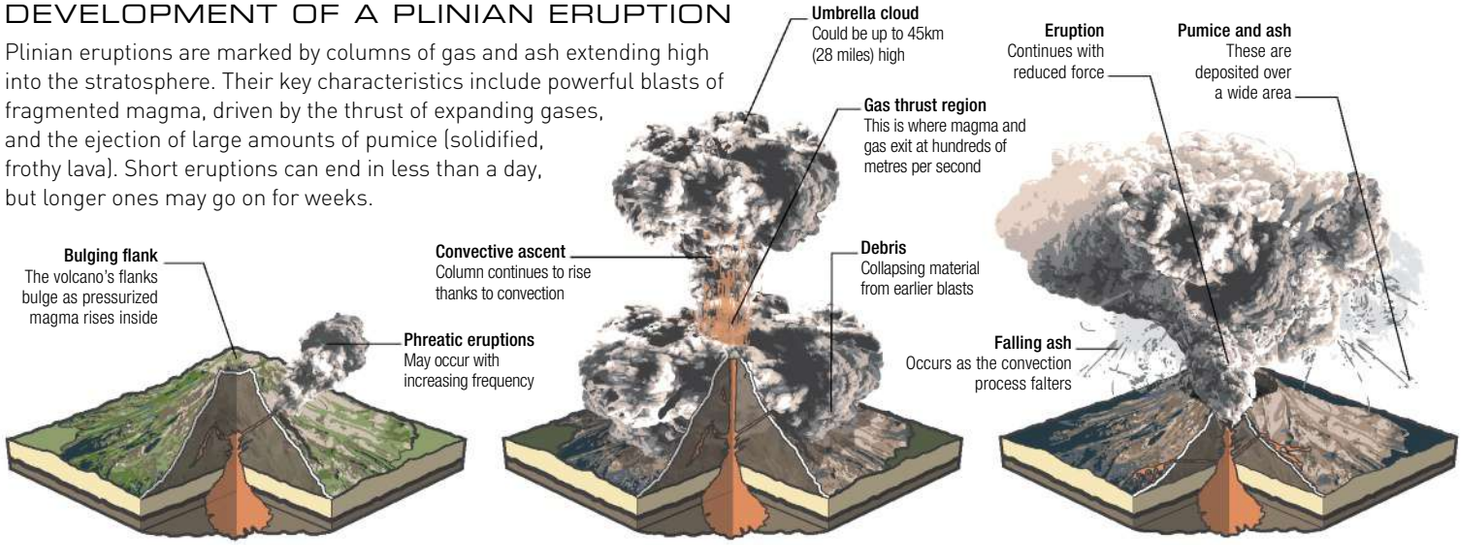
VOLCANO	DATE	VEI
Vesuvius, Italy	79CE	5
Tambora, Indonesia	1815	7
Novarupta, USA	1912	6
Hekla, Iceland	1947	4
Mount St Helens, USA	1980	5
Pinatubo, Philippines	1991	6
Chaitén, Chile	2008	4
Sarychev, Russia	2009	4
Eyjafjallajökull, Iceland	2010	4



SARYCHEV ERUPTION
In June 2009, astronauts aboard the International Space Station were treated to this view of Sarychev's eruption on Russia's Kuril Islands. The ash plume at one point reached a height of 12km (7 miles).

DEVELOPMENT OF A PLINIAN ERUPTION

Plinian eruptions are marked by columns of gas and ash extending high into the stratosphere. Their key characteristics include powerful blasts of fragmented magma, driven by the thrust of expanding gases, and the ejection of large amounts of pumice (solidified, frothy lava). Short eruptions can end in less than a day, but longer ones may go on for weeks.



1 BUILD UP TO ERUPTION

Rising magma and pressure build up in the volcano can cause ground deformation, gas or steam emissions, or small ash emissions along with loud bangs.

2 MAIN ERUPTION PHASE

Explosive eruption begins with large amounts of magma blasted skywards, often accompanied by loud detonations. Ash and pumice may be blown sideways.

3 ASH FALLOUT

As the eruption continues with reduced force, wind carries the ash cloud hundreds of kilometres, spreading ash fall over vast regions.



THE TAMBORA ERUPTION

The eruption of Tambora, in Indonesia, in 1815 ranks as the largest volcanic eruption in the last 1,800 years. It is also the most lethal of all time in terms of human deaths caused locally. The eruption was so large that it is classified as ultraplinian. During its main phase, three fiery columns were observed rising up into the air and merging. An estimated 160 cu km (38.5 cu miles) of ash and rock were shot into the atmosphere, followed by devastating pyroclastic flows. Close to 12,000 people were killed directly by the eruption; a further 60,000 to 80,000 are estimated to have died subsequently from starvation due to loss of crops and livestock. The ash spewed into Earth's atmosphere lowered temperatures worldwide. In the northern hemisphere, livestock died and crops failed, causing the worst famine of the 19th century.



CALDERA OF TAMBORA

Located on the island of Sumbawa, Tambora has returned to the quiescent state it maintained for 5,000 years before the 1815 eruption. Its caldera is 6km (4 miles) across and 1.1km (0.7 mile) deep. Active fumaroles, or steam vents, still exist on its floor.

VESUVIUS

One of the world's most dangerous volcanoes, Vesuvius is part of a volcanic region of Italy that results from the African Plate pushing under the Eurasian Plate. Although Vesuvius itself is a stratovolcano, it sits in the eroded caldera (collapsed remains) of an older, much larger volcano called Monte Somma. Sitting close to the Bay of Naples, Vesuvius has had various phases of activity and quiescence over the past few thousand years. Many violent eruptions occurred between 1631 and 1944, but there has been hardly any activity since. Today the volcano has to be closely monitored, since a large eruption, with less than a few days warning, could easily kill hundreds of thousands of people.

79CE ERUPTION

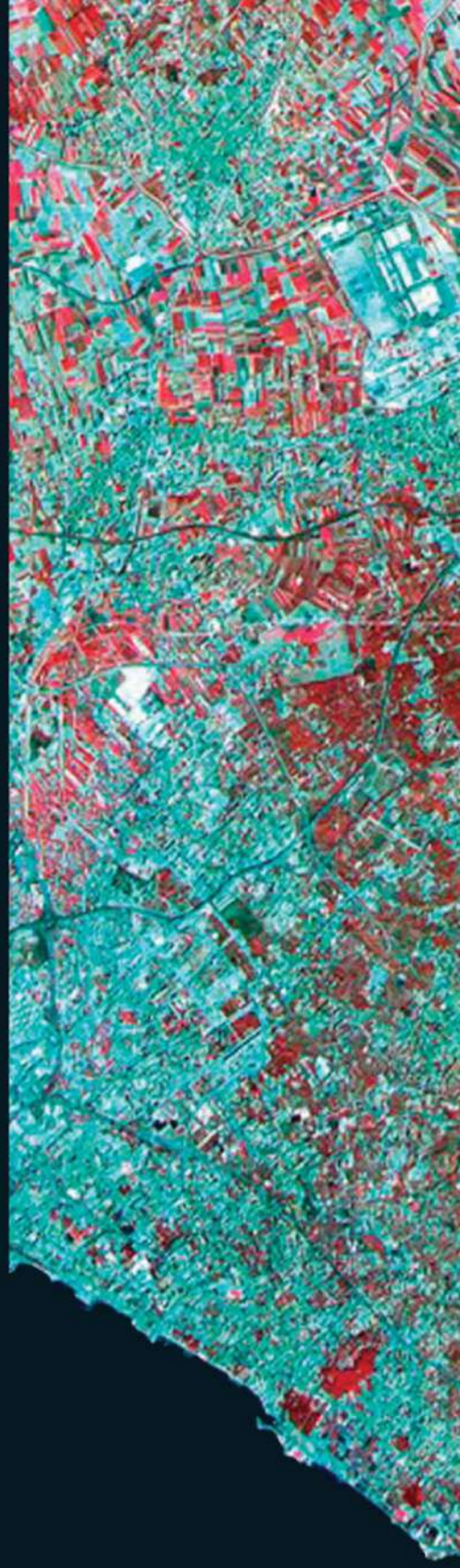
Vesuvius's largest eruption of the past 3,500 years, and its most famous, took place in 79CE. The eruption produced a huge ash cloud and ash falls, which together with a pyroclastic surge (see pp.28–29), killed about 2,100 people in the Roman towns of Pompeii and Herculaneum. Excavations of these towns over the past 200 years have revealed much about Roman life at the time.

> "THE CLOUD WAS RISING FROM... VESUVIUS. I CAN BEST DESCRIBE ITS SHAPE BY LIKENING IT TO A PINE TREE..."
>
> PLINY THE YOUNGER, DESCRIBING THE 79CE ERUPTION THAT KILLED HIS UNCLE, PLINY THE ELDER

79CE ERUPTION	
Location	Bay of Naples, Italy
Volcano type	Stratovolcano
VEI	5

2,100

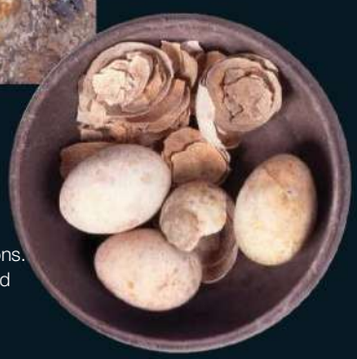
APPROXIMATE NUMBER OF FATALITIES



VESUVIUS FROM SPACE
In this false colour infrared satellite image, the cone and crater of Vesuvius appear turquoise at right of centre. The surrounding red region is the rest of the Vesuvius/Mount Somma complex. The light blue areas are built-up metropolis, while the Bay of Naples appears black.



SKULL FROM POMPEII
This skull of a victim of Vesuvius's 79CE eruption was discovered during excavations at Pompeii.



PRESERVED EGGS
This wooden bowl, with preserved eggs and eggshells, was unearthed during the Pompeii excavations. Other preserved foods found there include nuts and figs.

CAST OF MAN
This cast is of a man who died lying down at Pompeii while shielding his face – most probably to protect it from the extreme heat of the pyroclastic surge that buried him.



ERUPTION TIMELINE



1631 MASSIVE LAVA FLOWS
A large and sudden eruption occurred, marked by huge lava streams and pyroclastic flows that killed up to 4,000 people. People later mined the lava for building blocks.



1906 ASH CLOUD
A violent eruption, accompanied by earthquakes, produced a 13km- (8 mile-) high ash column, together with more lava than ever recorded before. At least 200 people were killed.



1944 AIRCRAFT DESTROYED
This eruption sent up a 5-km- (3-mile-) high ash plume and produced lava flows that invaded several villages. Heavy ashfalls destroyed US aircraft stationed at a nearby airport.

NOVARUPTA 1912

In June 1912, the most powerful volcanic eruption of the 20th century occurred in a sparsely populated region of Alaska. Over a period of 60 hours, some 13 cu km (3 cu miles) of magma was blasted into the air from a previously unknown, probably new, volcanic vent, later named Novarupta ("new eruption"). A thick layer of ash was deposited over hundreds of square kilometres of the Alaska Peninsula, and for three days complete darkness prevailed throughout the region. Remarkably, no one is known to have been killed and few witnessed the eruption, because of its remote location, although the blast was heard up to 1,200km (746 miles) away. The Novarupta vent lies close to a stratovolcano called Mount Katmai. Most of the erupted magma is thought to have drained from a magma reservoir beneath Katmai, which caused the upper half of the stratovolcano to disintegrate. The Novarupta vent itself became filled with a large plug dome.



6-8 JUNE 1912	
Location	Alaska Peninsula, Alaska
Eruption type	Plinian
VEI	6

30 BILLION

CU M (1,060 BILLION CU FT) OF ASH, DUST, AND CINDERS DEPOSITED IN THE REGION

VALLEY OF TEN THOUSAND SMOKES

A major feature of the Novarupta eruption was a massive pyroclastic flow. This surged into a valley to the north west of the eruption site, covering an area of about 100 sq km (40 sq miles) in ash up to 200m (650ft) thick. Thousands of hissing steam plumes rose from the mass of hot ash as it cooled. When the first scientific expedition to the area arrived four years later, the steam plumes were still very much in evidence, prompting one of the investigating scientists, Robert Griggs, to name it the "Valley of Ten Thousand Smokes".

POST-ERUPTION EVENTS



1 CLOUDS OVER MOUNT KATMAI
A photograph taken several months after the eruption showed clouds of steam and ash still rising from the partially collapsed Katmai volcano.



2 SCIENTISTS AT WORK
Surveys of the Valley of Ten Thousand Smokes and the surrounding area took place from 1916 to 1921.



KATMAI CALDERA ICED OVER
This lake-filled caldera, about 4.5km (2.8 miles) wide, is what remains of the Katmai stratovolcano, which catastrophically subsided during the Novarupta eruption.





3 STEAMING LAVA DOME
A hot, but inactive lava dome, emitting steam plumes, was found in the area between the Katmai stratovolcano and the ash-filled valley. This was later identified as a plug in the eruption vent.



4 ASH DEPOSIT EXPOSED
Over the decades, streams and rivers cut down through the thick deposits of pink volcanic ash. The valley shown here is 40m (130ft) deep.





5 LAVA DOME TODAY
The lava dome that plugs the Novarupta vent site is a black craggy mass about 90m (295ft) high and 360m (1,180ft) wide.

"HAVING REACHED THE SUMMIT OF KATMAI PASS, THE VALLEY OF TEN THOUSAND SMOKES SPREADS OUT... MY FIRST THOUGHT WAS: WE HAVE REACHED THE MODERN INFERNO."

JAMES HINE, A ZOOLOGIST ON THE FIRST EXPEDITION TO REACH THE ERUPTION SITE

MOUNT ST HELENS

In May 1980, the most famous volcanic event of the 20th century occurred in Washington state, USA, when the stratovolcano Mount St Helens lost most of its northern flank. An eruption had been anticipated, because an enormous bulge, caused by injection of magma, had been growing for several weeks near the volcano's summit, accompanied by frequent steam explosions. But what actually happened surprised everyone. At 8:32am on 18 May, an earthquake caused a gigantic chunk of Mount St Helens' summit and northern flank to suddenly disintegrate and slip away in the largest landslide in history. The landslide exposed the magma body, which exploded in a devastating sideways explosion, called a directed blast.



18 MAY 1980

Location	Cascade Range, Washington State, USA
Volcano type	Stratovolcano
Eruption type	Plinian

1,600

MULTIPLE BY WHICH THE ERUPTION BLAST EXCEEDED THAT FROM THE ATOMIC BOMB DROPPED AT HIROSHIMA IN 1945





BEFORE AND AFTER
As a result of the 1980 eruption, the once-graceful cone and summit of Mount St Helens (top) was scarred with an enormous ugly crater that had opened up on its north side (below).

A MOUNTAINSIDE EXPLODES
At the height of the eruption, a huge plume of ash rose some 24km (14 miles) into the air, driven by expansion of gas in the volcano's vent. Most of the ash eventually settled over a vast region of the northwestern United States.

MONITORING MOUNT ST HELENS

Since its May 1980 eruption, Mount St Helens has had further periods of eruptive activity, though it has been quiescent since 2008. The volcano is monitored by scientists from the US Geological Survey and other organizations. A particular watch is kept on earthquake activity close to the volcano, which could indicate new movements of magma, or any signs of surface deformation. Much of the monitoring is performed by automated sensors installed on and around the volcano.



CONSTANT WATCH
One way of remotely monitoring changes in Mount St Helens' shape is by measuring distances from a fixed point to devices installed on the volcano's flanks. Here a geologist is setting up equipment to perform such measurements.

> "I HAD JUST STARTED TO DRIVE ONTO THE OVERPASS AND THERE IT WAS... IT WAS LIKE WATCHING THE END OF THE WORLD COME SLOWLY."
>
> **LEE HARRIS**, DRIVING NEAR AUBURN, WASHINGTON, 120KM (75 MILES) FROM MOUNT ST HELENS, WHEN THE ERUPTION BEGAN

THE EFFECTS

The blast from the initial explosion immediately flattened all trees within a fan-shaped area extending for about 30 km (20 miles) north from the volcano's summit. Meanwhile, material from the landslide and exploding magma created a gigantic pyroclastic flow, which, moving at 1,000kph (600mph), pulverized and incinerated everything over an area of 600 sq km (230 sq miles). As this impacted a lake in its path, the water flashed to steam, creating a second larger explosion that was heard thousands of kilometres away, in northern California. Within minutes, millions of tonnes of melted glacier ice from the summit of the volcano mixed with ash and disintegrated rock to produce several devastating lahars (fluid mudflows). These surged down local rivers, destroying everything in their path, including bridges, trees, and buildings. By the time everything had settled, 57 people had perished – most by asphyxiation or incineration by the pyroclastic flow – and more than a billion dollars in damage had been done.



MUDFLOW DEPOSITS
The volcanic mudflows, or lahars, that surged down local rivers, sweeping away everything in their path, eventually slowed to a trickle, leaving thick deposits of mud and ash.





MOUNT ST HELENS
Smashed, burnt, and blasted trees covered the terrain surrounding Mount St Helens after its eruption on 18 May 1980. The initial sideways blast of hot gas, ash, and rock from the volcano knocked down about 600 sq km (230 sq miles) of forest, killing every tree in this area within 60 seconds.

PHREATIC ERUPTIONS

When heated volcanic rocks encounter groundwater or other surface water, the result may be a phreatic eruption – an explosion of steam and rock fragments. Another distinct type of eruption, termed phreatomagmatic, occurs when magma (molten rock) contacts water.

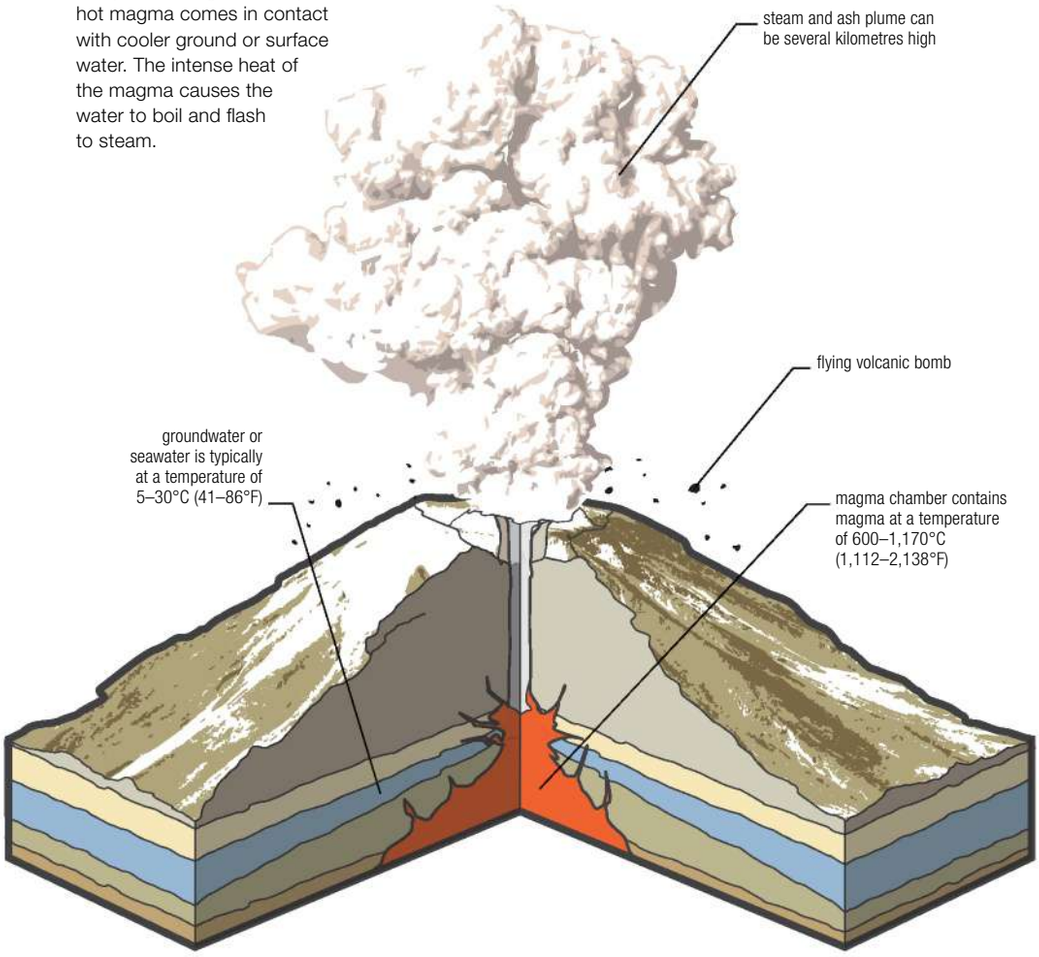
CAUSES AND FEATURES

Phreatic eruptions, also known as steam blast or ultravulcanian eruptions, can occur in any situation in which groundwater or other surface water comes into contact with volcanically heated rock or freshly deposited volcanic ash. These eruptions vary considerably in size and strength. Some herald larger eruptions – for example, several phreatic eruptions preceded the famous Plinian-style eruption at Mount St Helens, USA, in May 1980. Usually, the eruptive column is predominantly white due to the high steam content. Phreatic eruptions do not produce any fountains or streams of lava (see pp.22–25), but flying volcanic bombs (see pp.26–27) are fairly common.

Phreatomagmatic eruptions occur when quantities of groundwater, seawater, or other surface water come in contact with magma. A common scenario leading to a phreatomagmatic eruption occurs when magma rises into a layer of rock that has become saturated with groundwater. The 1883 eruption of Krakatau in Indonesia, one of the largest in recorded history, is often suspected to have been a phreatomagmatic eruption. A wall of the volcano ruptured, allowing seawater to flood into its magma chamber.



STEAM-DRIVEN ERUPTION
In a phreatomagmatic eruption, hot magma comes in contact with cooler ground or surface water. The intense heat of the magma causes the water to boil and flash to steam.





TOXIC WATER
Phreatic eruptions commonly occur from this crater lake – the world's largest acidic volcanic lake – within the Ijen volcano complex in Indonesia.

GUAGUA PICHINCHA
Located close to Ecuador's capital, Quito, this volcano has produced many large phreatic eruptions in recent decades. Its October 1999 eruption (seen here) caused a sizeable ashfall, which blanketed Quito.



HAZARDS

A number of dangers arise from phreatic and phreatomagmatic eruptions. A major hazard is the emission of large quantities of carbon dioxide, which can asphyxiate at high concentrations, and hydrogen sulphide, which is poisonous. In February 1979, for example, a phreatic eruption from the Dieng volcano in the central highlands of Java, Indonesia, killed 149 people due to carbon dioxide asphyxiation. Crater lakes on volcanoes that experience repeated phreatic eruptions are often highly acidic due to the presence of sulphuric acid produced by reactions between water and sulphurous volcanic gases. During eruptions from such lakes, highly acidic rain may fall from the sky. Another hazard with these eruptions is volcanic bombardment. In 1924, an eruption from the shield volcano Kilauea in Hawaii hurled massive boulders up to a kilometre (¾ mile) from the crater.

VOLCANOES PRONE TO PHREATIC ERUPTIONS



POÁS VOLCANO
A highly active stratovolcano in Costa Rica, the Poás volcano produces frequent phreatic eruptions, most recently in 2009. The floor of its crater contains one of the world's most acidic lakes.

MOUNT TARUMAE
Located within the Shikotsu caldera in Hokkaido, Japan, this active stratovolcano has produced a number of phreatic explosions in the last few centuries.



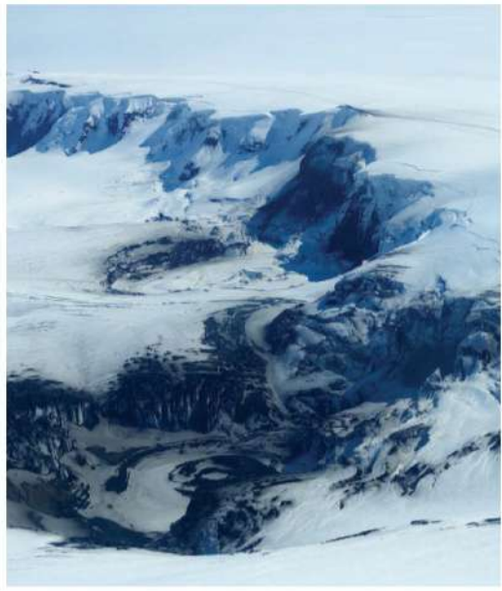
SUBGLACIAL VOLCANOES

A few of the world's volcanoes lie buried under enormous glaciers, in the form of ice caps or ice-sheets. Most are found either in Iceland, lying under one of its large ice caps, or in Antarctica. Eruptions of these volcanoes can have spectacular, but occasionally catastrophic, results.

ERUPTIONS UNDER ICE

Although some huge volcanoes lie under the West Antarctic ice sheet (see pp.98–99), none have erupted in thousands of years, so recent subglacial eruptions have been confined to Iceland. The heat from hot gases and magma coming up through the volcano causes the overlying ice to melt. The meltwater quickly cools the erupting magma, resulting in pillow lava (see pp.22–23). Once a hole has been melted in the ice all the way up to the glacier's surface, the eruption becomes visible in the form of a huge plume of steam and ash – produced by the explosive interaction of hot magma and water – shooting up into the atmosphere.

GRIMSVÖTN VOLCANO
Grimsvötn is a huge caldera volcano lying largely beneath Iceland's most extensive ice cap, Vatnajökull. Part of Grimsvötn's southern rim, visible here, lies just outside the ice cap.

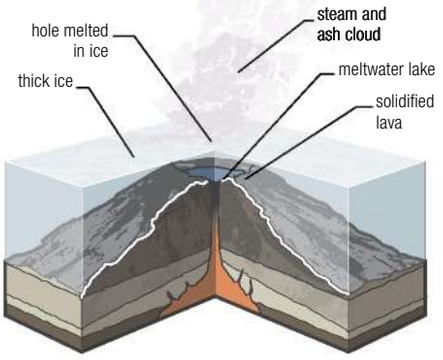




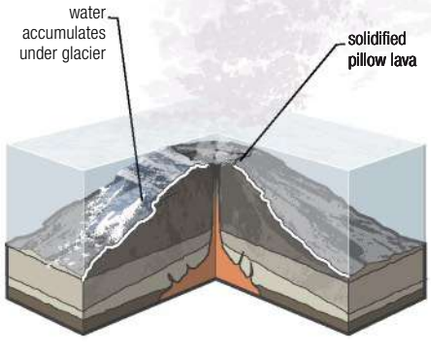
VATNAJÖKULL ICE CAP
This satellite photograph shows an ash plume rising from the western half of Vatnajökull as the result of a 2004 eruption of Grimsvötn.

PLUME FROM GRIMSVÖTN
The plume of steam and ash from the 2004 eruption of Grimsvötn rose to a height of 10km (6 miles). The eruption is thought to have started from a fissure in the subglacial caldera. Within a few days, it had melted a hole through 200m (660ft) of ice.

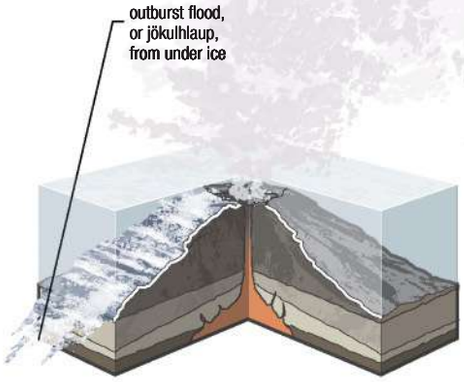
ERUPTION AND FLOOD



1 SUBGLACIAL ERUPTION
Heat from hot gases and magma coming up through the volcano melts a hole in the overlying ice. The released water cools the rising magma to form pillow lava.



2 WATER ACCUMULATION
The released water can become trapped as a lake under the glacier. As the eruption continues and the lake enlarges, it may even start to slightly lift the glacier, even though this may weigh billions of tonnes.



3 GLACIAL OUTBURST FLOOD
Eventually the lake becomes so large, and the buildup of pressure so great, that the water suddenly bursts out, either by flowing out under the glacier (as shown here) or exploding out through its side.

JÖKULHLAUPS

In most subglacial eruptions, the water produced from melted ice becomes trapped as a lake between the volcano and the overlying glacier. Eventually, this may be released in a violent and dangerous flood. Events of this type are so common in Iceland that Icelanders have a specific term for them – "jökulhlaup", or "glacial outburst flood". One of the most dramatic jökulhlaups in Iceland of all time occurred in 1996 as a result of an eruption of Grimsvötn. Over three or four weeks, more than 3 cu km (0.7 cu miles) of meltwater accumulated beneath the Vatnajökull ice cap. The subglacial lake suddenly burst out, some of the water escaping beneath the ice cap and some blasting out through a fissure in its side. The resulting flood was temporarily the second biggest flow of water in the world (after the River Amazon). It caused $14 million of damage and left numerous 10-m- (33-ft-) high icebergs – chunks of the Vatnajökull ice cap –scattered across Iceland's coastal plain.

TUYA



HERÐUBREIÐ TUYA, ICELAND
A subglacial volcano develops steep sides and a flat top due to the way lava builds up at at its summit, constrained by ice. After the volcano becomes extinct, and the ice cover retreats, a landform with this shape, called a tuya, is left.



RUSH OF MELTWATER
During the eruption of the Eyjafjallajökull volcano in Iceland in 2010, meltwater rushed out from under the edges of the ice cap overlying the volcano to produce lakes and some jökulhlaups.



VOLCANIC LIGHTNING
Eyjafjallajökull's ash plume was frequently illuminated by dramatic electrical discharges, thought to be the result of untold numbers of collisions between ash and ice particles generating static electricity.

EYJAFJALLAJÖKULL

For several weeks in April and May 2010, a previously little-known Icelandic volcano became a focus of attention in Europe as it belched huge quantities of ash into the atmosphere, bringing air traffic across a large part of the continent to a standstill. The eruption of the volcano – which lies partly under the small Icelandic ice cap of Eyjafjallajökull (Icelandic for "island mountain glacier") – had started off in a low-key way with the appearance of fissures near a mountain pass next to the glacier, together with some lava fountaining. But a few weeks later, on 14 April, the eruption moved up to the summit crater underneath the ice itself and entered a new, explosive phase with the ejection of fine, glass-rich ash to a height of 8km (5 miles) in the atmosphere. This was a Plinian-style eruption, though in Iceland only considered moderately big compared with some of the monstrous eruptions the country has seen in the past. What was worrying Icelanders, and others, was that it might soon be followed by activity at Eyjafjallajökull's larger and more dangerous neighbour, a huge caldera volcano called Katla.



APRIL–MAY 2010	
Location	Southern Iceland
Volcano type	Stratovolcano
Eruption type	Plinian
VEI	4
People displaced	500 families

95,000
SCHEDULED PASSENGER FLIGHTS CANCELLED

AIR TRAFFIC DISRUPTIONS

The location of the eruption meant that the ash was carried into the heavily used airspace over northwestern Europe, and from 15 April 2010, aviation authorities closed much of the airspace in this region. This situation continued for the next eight days, stranding 10 million passengers and causing damage to some European economies. After 23 April, the affected airspace was reopened, but closures continued to occur intermittently in different parts of Europe as the ash cloud was monitored using technology such as lidar (see right). In Iceland, the eruption of Eyjafjallajökull had stopped by the end of June 2010, and as of May 2011, there had been no follow-up eruption of Katla.



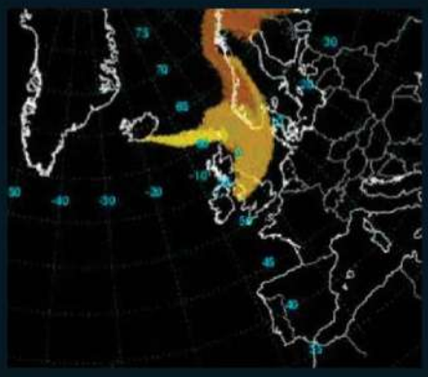
STUDYING THE ASH
An engineer demonstrates a lidar (light detection and ranging) device – laser-based technology that can be used to gather data on atmospheric particles. Lidar proved particularly useful in studying the ash plume.



AVIATION HAZARD
Even when it has been dispersed to the point of being invisible, volcanic ash poses grave dangers to aircraft. Ash particles can melt inside jet engines and force engine shutdown. They also abrade windscreens and clog vital sensors.

> "SUDDENLY... YOU REALIZE THAT ALL ALONG YOU HAVE BEEN INHABITING THE EARTH."
>
> **FRENCH ANTHROPOLOGIST BRUNO LATOUR**, *A PLEA FOR EARTHLY SCIENCES*, KEYNOTE SPEECH AT THE BRITISH SOCIOLOGICAL ASSOCIATION, 2007

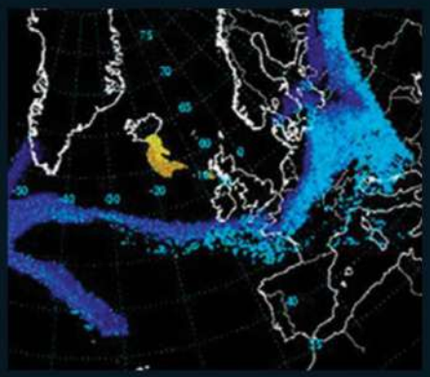
THE PLUME SPREADS



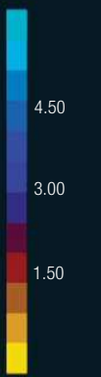
1 15 APRIL 2010
The plume had spread to cover much of Norway and northern England and was impinging on other Scandinavian countries. Most airspace in the British Isles, Norway, and parts of Sweden had by now been closed.



2 18 APRIL 2010
There was now an extensive cloud of two- to three-day-old ash over much of the British Isles, France, and central Europe, with a new pulse heading in. Airspace was now closed, or partially closed, in 20 countries.



3 20 APRIL 2010
Following a period of relative quiescence at the volcano, the area of new ash was much reduced, though a cloud of older ash covered eastern Europe. A few days later most of the formerly closed airspace was reopened.



MEAN AGE OF ASH PARTICLES IN DAYS





ERUPTION OF EYJAFJALLAJÖKULL
An angry, billowing plume of hot ash and steam rises up through a fissure in the Eyjafjallajökull ice cap, from the volcanic vent lying underneath, and is blown horizontally towards the sea. All around the fissure, a grubby deposit of ash lies on the ice. The erupted ash was of a fine, abrasive, glass-rich type, making it particularly dangerous to aviation.

ANTARCTIC VOLCANOES

It might seem odd to think of volcanoes in a place as chilly as Antarctica, but for red-hot magma rising up towards Earth's surface, the cold of Antarctica is no barrier. This continent has about 30 volcanoes, only a few of which have recently been active.



TOWER OF ICE
On the flanks of Erebus are fumaroles that have formed strange ice towers. As steam emerges from a vent, some of it condenses to form water. As this flows towards the ground, it quickly freezes, adding more ice to the tower.



STEAM PLUME
A small steam plume emanates from the summit of Erebus, which is almost entirely covered by ice. On its more active days, Strombolian explosions may hurl small lava bombs onto its upper slopes.

MOUNT EREBUS

Antarctica's most active volcano, Mount Erebus, is also the most southerly to have erupted in recorded history. The 3,794-m- (12,447-ft-) high stratovolcano is located on Ross Island, off the coast of East Antarctica, along with three other, apparently inactive, volcanoes. All four are thought to sit over a hotspot under the Antarctic Plate. Erebus is one of a few volcanoes to have a lava lake in its summit crater. It was erupting when first sighted by Captain James Ross in 1841, and is still erupting today. It produces frequent minor explosions in its lava lake and occasional larger Strombolian explosions (see pp.74-75).



WEST ANTARCTIC VOLCANOES

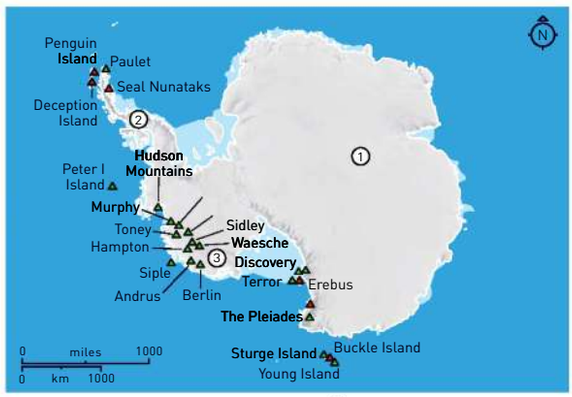
In an area called Marie Byrd Land in West Antarctica lies a group of large volcanoes almost completely buried in ice. This group is thought to be the result of a 3,200-km- (2,000-mile-) long continental rift opening up under the West Antarctic ice sheet. Some West Antarctic volcanoes, such as Mount Hampton, are probably extinct, but others, such as Mount Takahe – which is thought to have erupted about 7,000 years ago – are potentially active. In 2008, scientists found evidence of a relatively recent eruption, about 2,000 years ago, beneath the Hudson Mountains in West Antarctica. Using ice-sounding radar, they discovered a layer of ash from the eruption lying beneath the ice sheet.



MOUNT HAMPTON
The only visible part of this massive shield volcano is its summit area. This is largely occupied by a 6-km- (4-mile-) wide crater, which is completely filled with ice.

VOLCANOES IN THE FROZEN CONTINENT

Antarctica's volcanoes fall into three main groups – one around the tip of the Antarctic Peninsula, a second in West Antarctica, and a third near the coast of East Antarctica. The massive stratovolcano Mount Melbourne is the only recently active volcano on the Antarctic mainland. Mount Erebus is on an island. The Seal Nunataks, a group of nunataks (mountain tops poking above the ice) near the Antarctic Peninsula, are thought to be separate volcanoes or remnants of a large shield volcano.





DECEPTION ISLAND
Consisting of a horseshoe-shaped flooded caldera (see pp.52–53), Deception Island last erupted between 1969 and 1970, destroying two scientific stations. It is one of the South Shetland Islands, an arc of volcanic islands that lie along a convergent plate boundary near the Antarctic Peninsula.

AFRICAN RIFT VOLCANOES

Continental rifts are regions of Earth's surface that are pulling apart. The rifting is associated with plumes of hot mantle rising up from the interior. As a result, volcanoes often form in such regions. Those found in the East African Rift Zone are some of the most spectacular volcanoes on the planet.

EASTERN RIFT VOLCANOES

The eastern part of the rift system, called the Eastern Rift Valley, contains a handful of volcanoes, including Ol Doinyo Lengai. It is the only volcano in the world to erupt natrocarbonatite – the most fluid and coolest of all lavas, with a temperature of about 500°C (930°F). Although black or brown, it turns white on contact with moisture. Near Lengai lies Kilimanjaro, which consists of a complex of three stratovolcanoes. Although no eruptions have been recorded, it contains a magma chamber 400m (1,310ft) below its crater, and future eruptions are not ruled out. Other volcanoes include The Barrier in Kenya composed of four overlapping shield volcanoes, and a stratovolcano, Meru.



EAST AFRICAN RIFT SYSTEM
This region has three main volcanically active areas – the Eastern Rift Valley, the Western Rift Valley, and the Afar Depression in the north.

OL DOINYO LENGAI, TANZANIA
Known as "Mountain of God" in the language of the native Masai people, Ol Doinyo Lengai produces a unique form of lava that glows a vivid orange at night. Here, lava can be seen oozing from one of the steep-sided cones that have formed in the volcano's summit crater.



SUMMIT CRATER
Ol Doinyo Lengai's crater is filled with solidified lava, which appears white by day. The volcano's eruptive activity is usually centred on small lava flows from the cones on the crater's floor. Occasionally, this pattern changes to more violent eruptions with ash plumes and larger lava flows.

THE VIRUNGA VOLCANOES

In the Western Rift Valley, within the Virunga Mountains west of Lake Victoria, lie two dangerous volcanoes, responsible for about 40 per cent of Africa's volcanic eruptions and most volcano-related deaths. Mount Nyamuragira, Africa's most active volcano, is a shield volcano that has erupted more than 40 times since 1885, most recently in 2010. It is noted for producing large amounts of sulphur dioxide gas and toxic ash. Mount Nyiragongo, nearby, has a lava lake at its summit that has been described as a "boiling cauldron of hell". From time to time, the lava either erupts from the summit or bursts out of fissures on its flanks, flowing downhill at great speeds and killing anyone in its path. One of its most disastrous eruptions occurred in 2002 (see pp.102-103).



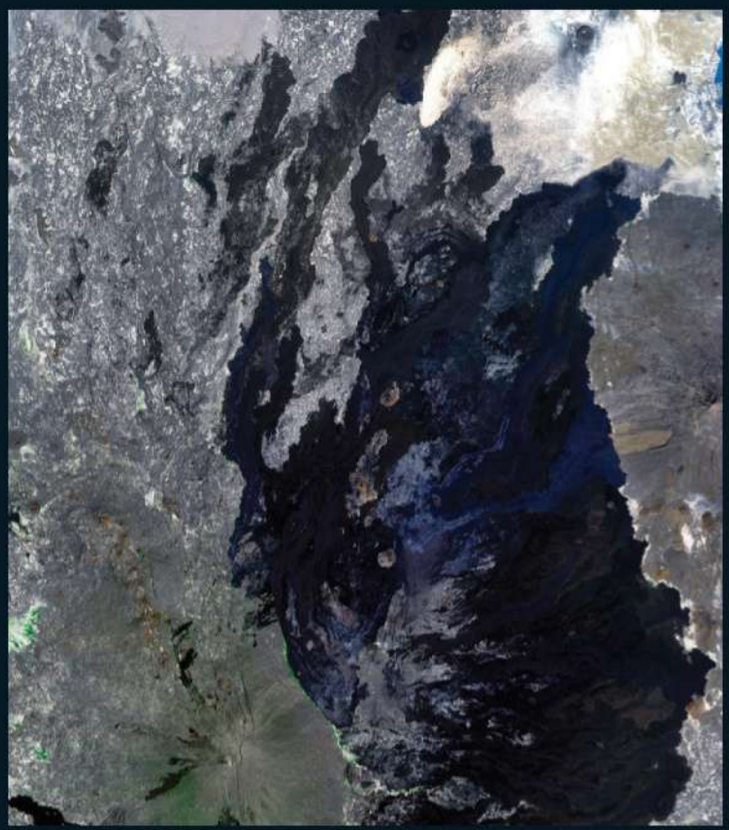
MOUNT NYIRAGONGO
This stratovolcano in the Democratic Republic of the Congo is 3,470m (11,384ft) high, with a 2-km- (1-mile-) wide summit crater, visible in this satellite photograph. It has erupted at least 34 times since 1892, and is dangerous due to its steep flanks and fluid lava.

VOLCANOES OF THE AFAR TRIANGLE

The Afar Triangle, or Afar Depression, is a barren region of northeastern Africa. It is situated well below sea level and is one of the hottest, driest, and most inhospitable places on Earth. It contains some notable volcanoes, the best known being Erta 'Ale (the Fuming Mountain or Devil's Mountain), which is a huge active shield volcano. At its summit lies a large, elliptical crater, measuring 700 by 1,600m (2,297 by 5,249ft), which contains two smaller steep-sided "pit" craters, one holding a spectacular lava lake. This lake occasionally produces dangerous eruptions, but because of its remoteness, the volcano is peculiarly hard to monitor. Other volcanoes and volcanic regions in the Afar Triangle include another large shield volcano, known as Alayta, and a region of hot springs and small volcanic craters called Dallol. Near the coast of the Red Sea is a stratovolcano called Dubbi, which erupted spectacularly in 1861. It produced lava flows that travelled for 22km (14 miles), and created a plume of ash that fell as far as 300km (186 miles) from the volcano. This was Africa's largest eruption in the past several hundred years and killed more than 100 people.



ERTA 'ALE, ETHIOPIA
The most famous feature of Erta 'Ale is a fiery, circular lava lake with a 150m (500ft) diameter. When fully molten, it produces lava fountains and gives off large amounts of heat. At other times, a solid crust forms over much of the lake's surface.



ALAYTA VOLCANO
This large shield volcano in the western part of the Afar Depression covers more than 2,700 sq km (1,040 sq miles). In this satellite image, much of its surface looks black due to erupted lava. An eruption in 1907 led to considerable damage to land, property, and human life. Alayta last erupted in 1915.



NYIRAGONGO DISASTER

The 2002 eruption of Mount Nyiragongo was the most destructive flow of lava in modern history. Nyiragongo's lava is highly fluid, and when it escapes from a large lava lake at the summit, it races down the volcano's steep sides. In 2002, fissures opened up on the volcano's flanks and streams of lava, 200 to 1,000m (655 to 3,280ft) wide and up to 2m (6½ft) deep, oozed into Goma City, creating fires and explosions. Forty-five people died, some due to asphyxiation by volcanic gases, others following the explosion of a petrol station. About 12,000 people were left homeless.



JANUARY 2002	
Location	Democratic Republic of the Congo
Volcano type	Stratovolcano
Eruption type	Hawaiian
Explosivity index	1

350,000 THE NUMBER OF PEOPLE EVACUATED

ERUPTION CHRONOLOGY
Streams of lava burst from fissures on Mount Nyiragongo. One cut across the runway at Goma Airport, igniting aviation fuel, while others poured into the city and reached Lake Kivu.



KEY
Lava flows
Urban area
Airport

THE 2002 DISASTER



1 LAVA LAKE
Nyiragongo is the only steep-sided volcano that holds a lake of red-hot, extremely fluid lava at its summit. On this occasion, the lava suddenly drained from the lake through fissures that appeared on the volcano's flanks.



2 GOMA AIRPORT
Streams of hot fluid lava entered Goma Airport, covering the northern end of its runway, and then swept into Goma, destroying 45,000 buildings, including 90 per cent of the town's business district.



3 LAKE KIVU
Lava entered Lake Kivu, raising concerns that it might cause gas-saturated waters to rise from the bottom of the lake and release lethal amounts of carbon dioxide. Thankfully, the lava did not penetrate far enough.

"THIS MORNING, AN APOCALYPTIC SCENE. IT'S AS THOUGH A GIANT BULLDOZER HAS SWEPT THROUGH GOMA. THE FUMES... ALMOST OVERPOWERING."

ANDREW HARDING, BBC CORRESPONDENT, SURVEYING THE SCENE OF THE DISASTER

LAVA CASCADES
In this 2010 photograph, streams of lava cascade down Nyiragongo's flanks, in a similar, though slightly more subdued, manner to what happened in the 2002 eruption.

VOLCANIC REMNANTS

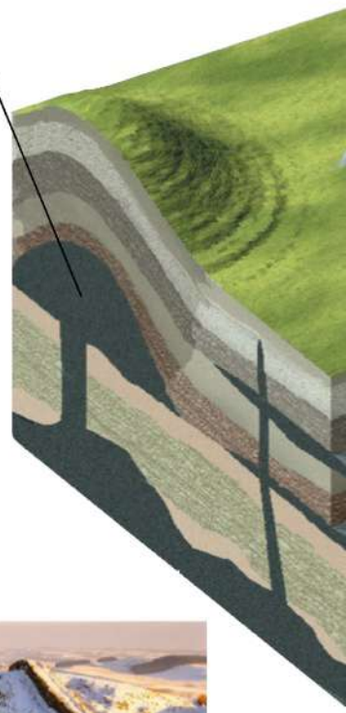
Volcanic activity leaves its mark on our planet in many ways. In addition to volcanoes and their eruptive products are the remains of ancient magma bodies that solidified inside volcanoes or deep underground and were later exposed at the surface through erosion.



SHIP ROCK
Made of hard rock types called lamprophyre (also known as minette) and volcanic breccia, Ship Rock is a volcanic plug with radiating dikes. It stands 482m (1,583ft) above the surrounding high-desert plain.

VOLCANIC PLUGS

These landscape features are the result of magma solidifying within the vent and other internal spaces in a volcano, to form a hard plug of igneous (magma-derived) rock. Later, when the rest of the volcano has eroded away, this plug is uncovered on the surface. A classic example is Ship Rock, in New Mexico, USA, the remains of a volcano that existed about 27 million years ago. When the magma that formed Ship Rock solidified, the plug was probably about 850m (2,800ft) below the surface. Subsequently, weathering and erosion removed the lava and ash layers of the volcano, together with underlying soft shales, to expose Ship Rock as it is today.



IGNEOUS INTRUSIONS
Magma that pushes up into any cracks and other spaces it can find in existing rock layers, sometimes forcing them aside, is called an igneous intrusion. Intrusions eventually cool to form solid bodies, which erosion may later expose at the surface as a variety of landscape features.

DIKES AND SILLS

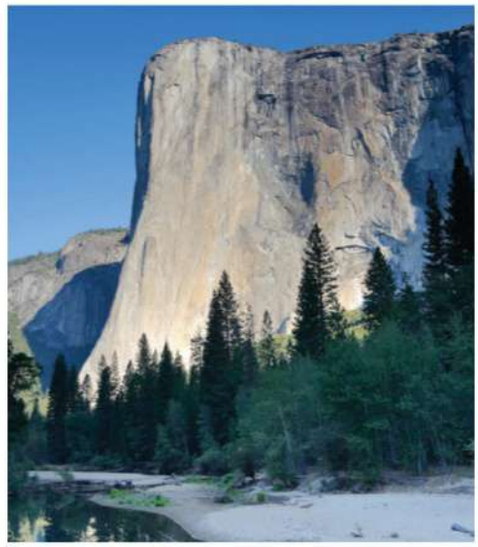
Two relatively small types of intrusion that are often exposed at the surface are dikes and sills. Both usually form from runny basaltic magmas, which can squeeze through thin gaps and cracks in country rock (rock that predates the intrusions). These magmas typically solidify to form a rock called dolerite. Dikes are thin, vertical intrusions that cut through horizontally bedded rock layers. They can take various forms, including those that radiate from a central point, ring dikes (encircle volcanic centres and are formed when magma is squeezed up through a ring fracture), or a series of parallel structures, called a dike swarm. Sills are horizontal structures that lie along bedding planes (boundaries between layers of sedimentary rock). An example is Whin Sill in England, which is exposed in a few places as outcrops about 30m (100ft) thick.



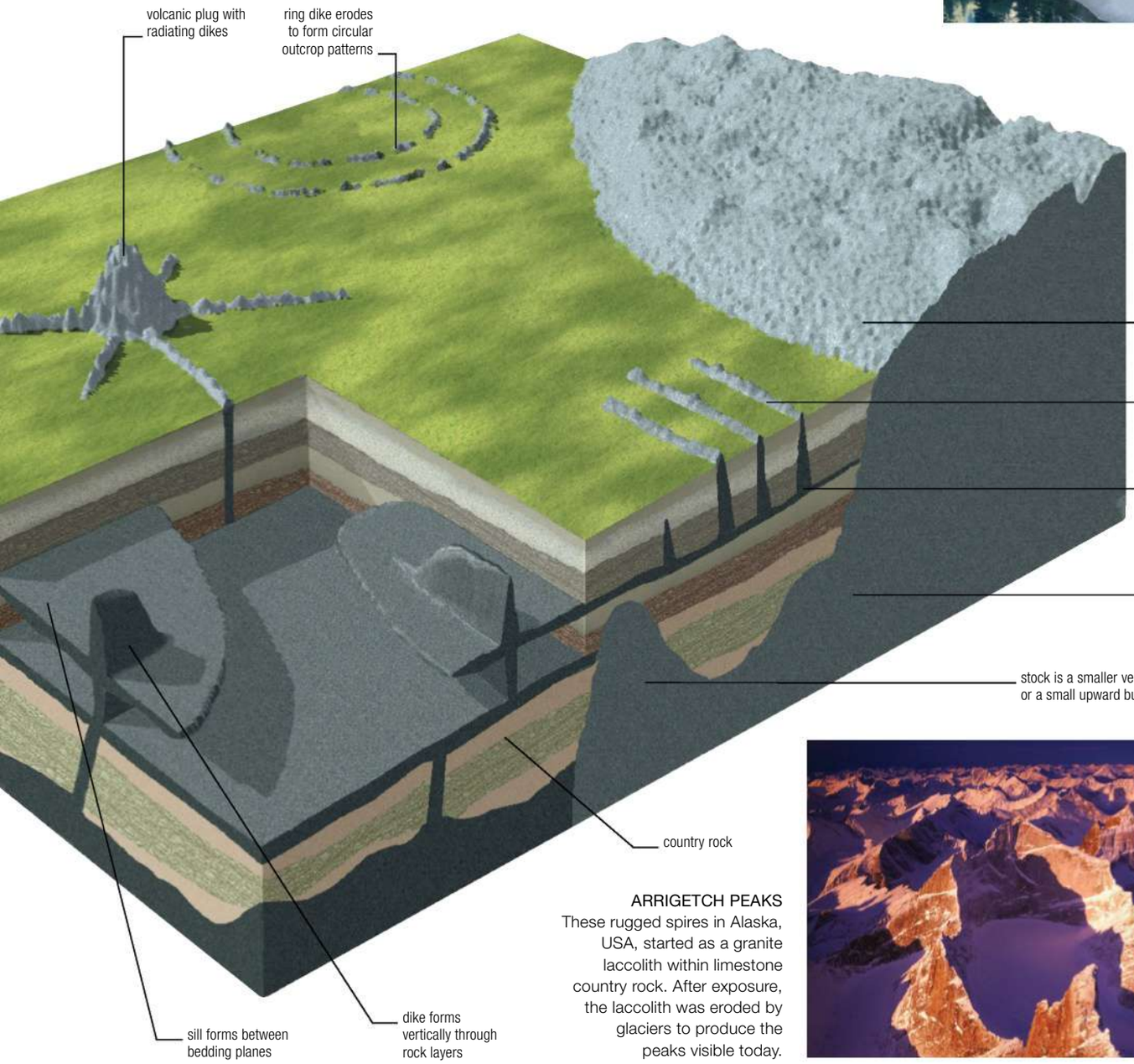
WHIN SILL
Hadrian's Wall was built on part of this exposed sill in northeastern England. The sill was intruded some 295 million years ago.

BATHOLITHS AND LACCOLITHS

Larger igneous intrusions include batholiths, laccoliths, and some minor types such as lopoliths and stocks. All of these are usually made from granitic magmas – these have a different composition from, and are more viscous than, basaltic magmas. As a result, they form huge masses underground instead of penetrating cracks and crevices. Batholiths are the biggest of the large igneous intrusions and are typically made of granite or related rocks. Once exposed at the surface, batholiths have an area of at least 100 sq km (40 sq miles), and many are much larger than this. Similar structures with areas less than 100 sq km (40 sq miles) are called stocks. An example of a batholith is the Sierra Nevada batholith in California, USA, which is some 600km (370 miles) long and consists of more than 100 individual bodies, called plutons. These were formed from the cooling of separate blobs of magma some time between 225 and 80 million years ago. Of the other types of large intrusion, laccoliths are large, lens-shaped intrusions that bulge upwards and are often composed of a rock called gabbro. Lopoliths are similar but sag downwards. The Pine Valley Mountains laccolith in Utah, USA, is one of the largest in the world.



EL CAPITAN
A part of the Sierra Nevada batholith, El Capitan is a 910-m- (3,000-ft-) high rock formation, made of solid granite in the Yosemite National Park, California, USA. It formed underground about 100 million years ago.



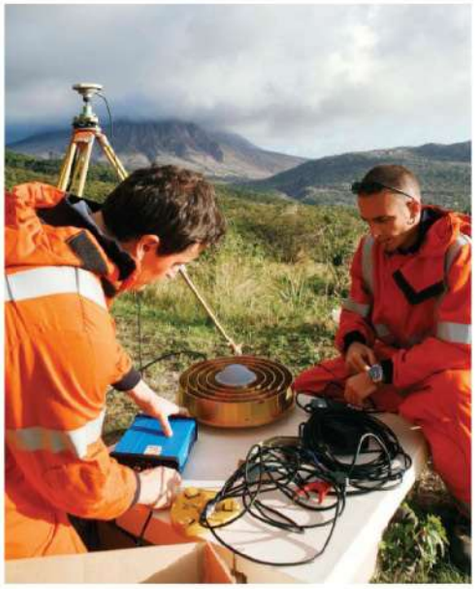
ARRIGETCH PEAKS
These rugged spires in Alaska, USA, started as a granite laccolith within limestone country rock. After exposure, the laccolith was eroded by glaciers to produce the peaks visible today.

MONITORING VOLCANOES

Many of the world's most dangerous volcanoes, especially those near cities, are monitored scientifically. Although volcanologists cannot predict precisely when or how a volcano will erupt, they can warn of an increased risk of an eruption and give an idea of its likely character.

METHODS AND TOOLS

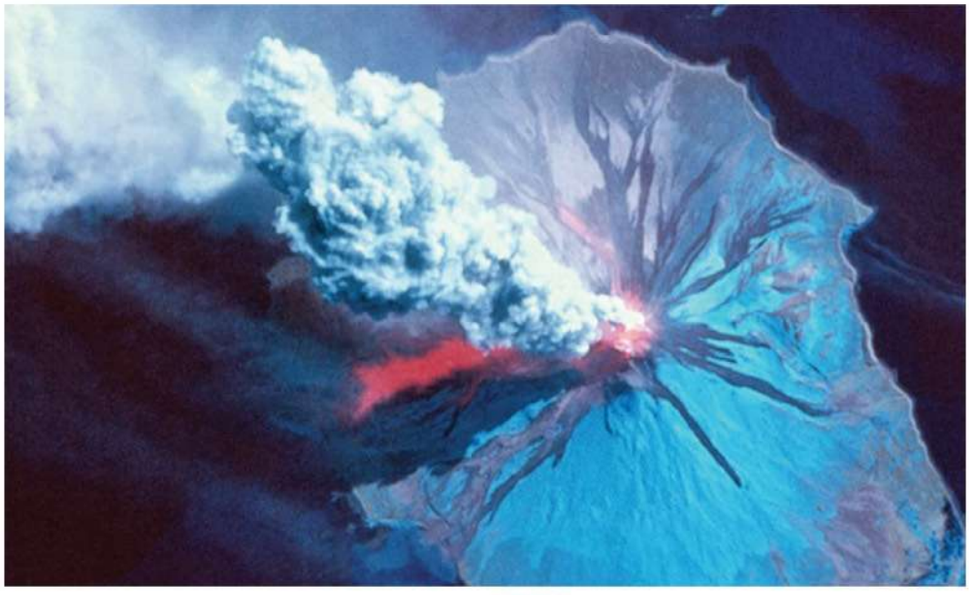
Volcanologists use several different methods to monitor volcanic activity. For example, they analyse the gases emitted by a volcano, use seismometers to detect tremors in the ground underneath it, and employ instruments called tiltmeters to measure any bulging on its flanks. Increased emission of certain gases, a rise in the frequency and intensity of earthquakes, or ground bulging, can all indicate that magma is welling up inside the volcano and are fairly reliable signs of an imminent eruption. Satellite surveillance is a more expensive alternative to measuring ground deformation. Other methods include monitoring for changes in magnetic field strength and gravity near a volcano, which may be used to trace magma movement. Once scientists have thoroughly studied a volcano, they produce hazard maps. These maps may show, for example, the most likely routes of future lava flows or lahars (volcanic mudflows). When the risk of eruption rises to a significant level, people can be advised to move away temporarily from the main danger zones or even to evacuate the entire area.



MONITORING STATIONS
Technicians set up equipment to measure ground deformation near the Soufrière Hills Volcano on the Caribbean island of Montserrat. This is one of the world's most heavily monitored volcanoes.



GAS SAMPLING
Volcanologists often measure and analyse the gases emitted by a volcano. A number of these gases are highly noxious so gas masks are worn.



REMOTE SENSING
Satellites are used to monitor erupting volcanoes, such as this explosion of Augustine volcano in Alaska. They track the extent and movement of ash plumes, which are a hazard to aviation.

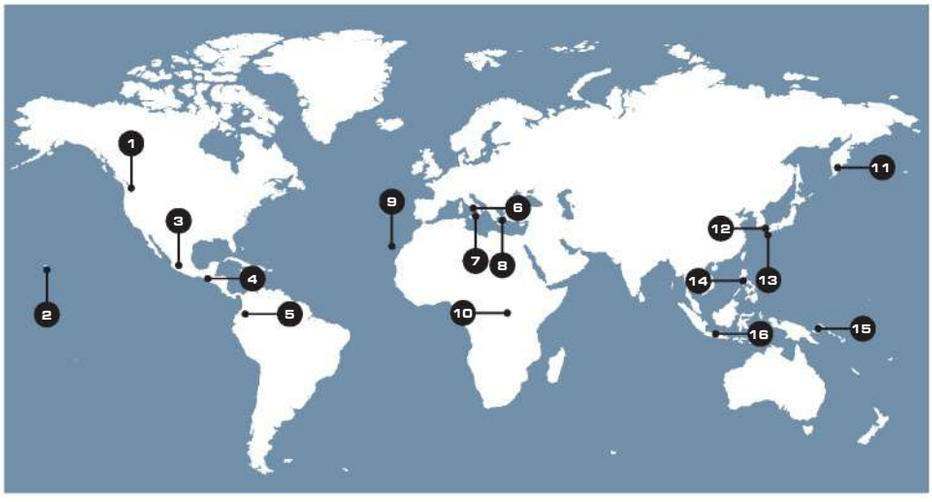


SPECIAL THERMOMETER
Thermocouple thermometers are used to measure the temperature of the ground, lava, or gases at a volcanic site. They can withstand temperatures from -200ºC to 1,500ºC (-358ºF to 2,732ºF).



FIELD WORK
Wearing a protective heat suit, this volcanologist is taking samples from a lava flow on Mount Etna. Changes in the temperature and composition of lava provide clues about the future course of an eruption.

VOLCANOES FOR SPECIAL OBSERVATION



The International Association of Volcanology has identified a group of 16 volcanoes known as “decade” volcanoes for particular study and monitoring because of their history of destructive eruptions and proximity to heavily populated areas. When selecting these volcanoes, additional criteria included the existence of multiple dangers, such as the risk of pyroclastic flows, lahars, and various types of collapse. Not all have received special monitoring so far, mainly due to funding difficulties.

1. Rainier
2. Mauna Loa
3. Colima
4. Santa María
5. Galeras
6. Vesuvius
7. Etna
8. Santorini
9. Teide
10. Nyiragongo
11. Avachinsky-Koryaksky
12. Unzen
13. Sakurajima
14. Taal
15. Ulawun
16. Merapi

LIVING WITH VOLCANOES

About 8 per cent of the world's population lives near a volcano, which is surprising given their reputation for danger. Despite the risks, millions of people put up with them, mainly for economic reasons.

HAZARDS

Analysis of the causes of deaths from volcanic eruptions over hundreds of years shows that the greatest dangers come from pyroclastic flows (see pp.28–29) and, for a few volcanoes, mudflows (see pp.32–33). Some volcanoes can cause gas poisoning and large eruptions near coasts can set off tsunamis. Heavy ashfalls can also be dangerous, but lava flows are generally more of an economic nuisance than a lethal hazard.



PICKING UP THE PIECES
A man recovers part of a zinc roof three days after an eruption of the Nyiragongo Volcano (see pp.102–103) caused widespread destruction.



MINING AND TOURISM

Against the risks they pose, volcanoes can bring some advantages. In the volcanic regions, the amount of heat flow coming out of Earth (geothermal heat) is high and this can be exploited as a carbon-free energy source. A few volcanoes are a source of other natural resources, such as sulphur and diamonds. They can also bring economic benefits to a region through tourism. The beauty and excitement of erupting volcanoes attracts hundreds of thousands of sightseers every year.



MINING SULPHUR
The Ijen volcano in Java, Indonesia, supports an industry in which volcanic gases are artificially converted to sulphur, which is then carried out of the volcano's crater. This provides employment, though the work is extremely arduous and involves health hazards.

AGRICULTURAL BENEFITS

An erupting volcano usually produces a great amount of ash, lava, or both. In the short term these can be harmful to the environment, but in the long term they decompose to form a fertile soil, containing many useful minerals. In the region around an active volcano, there is nearly always a sizeable group of people farming the soil. Even after a large and possibly lethal eruption, they return to reclaim their livelihood. This explains the high density of populations in volcano-dominated islands like Java and the settlements around dangerous volcanoes, such as Merapi, also in Indonesia.



CULTIVATED VOLCANO
Terraced wheat fields adorn the slopes of a small, probably extinct, volcanic cone in Rwanda. The fact that every bit of the volcano's surface is being used provides a good indication of the soil fertility here.



MAYON VOLCANO
The symmetrical cone of Mount Mayon in the Philippines is surrounded by a fertile agricultural region. People live near this dangerous volcano for the livelihood it provides, and also for the beautiful setting.



WITNESSING AN ERUPTION
Tourists admire and photograph the erupting Icelandic volcano, Eyjafjallajökull, in April 2010. More than 100,000 people, many from outside Iceland, went to see the eruption. The tourist influx boosted Iceland's economy.

ASH AND LAVA RECOLONIZATION

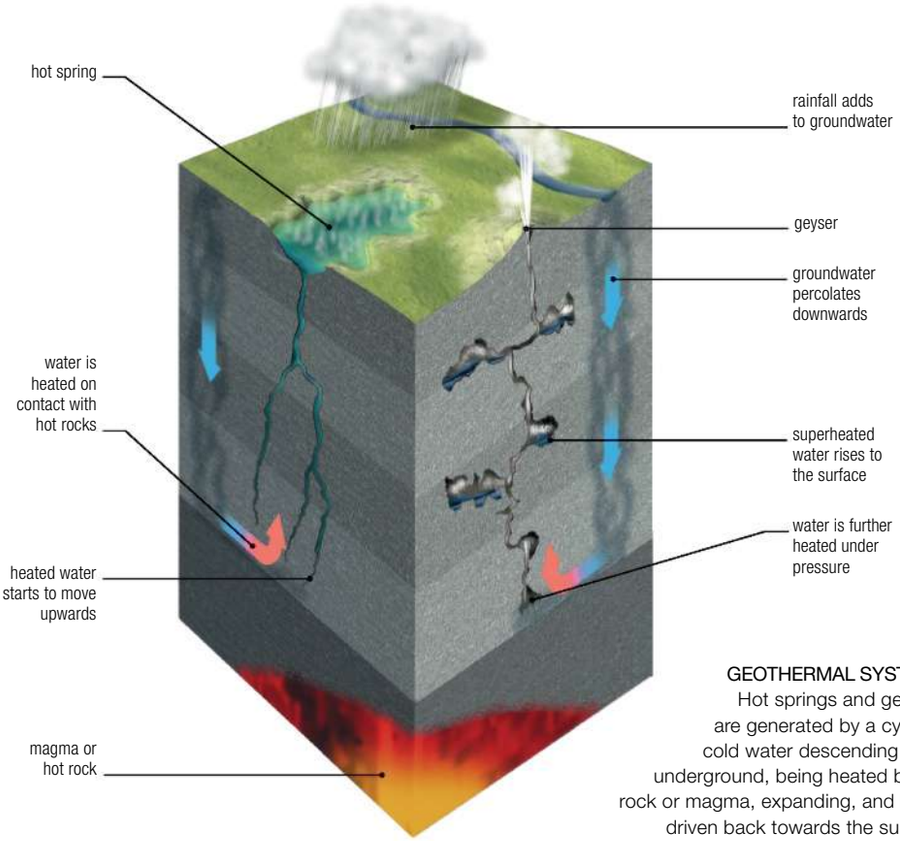
Despite the devastation they can cause, lava flows and ashfalls are usually quite rapidly recolonized by plants. Recolonization usually starts within 10 years for lava flows and within 3 to 4 years for ashfalls, emphasizing the additional fertility they can bring to soils.



Ferns in lava
This crack in a pile of pahoehoe lava, in which some ferns have recently started growing, was spotted on the Puna coast of Hawaii's Big Island.

VOLCANIC HOT SPRINGS

Hot springs form when large amounts of groundwater is heated by magma below the volcano. The presence of minerals and microbes can make these pools look colourful, but the water can often be at an extreme pH due to the volcanic gases that are in the system.



GEOTHERMAL SYSTEMS
Hot springs and geysers are generated by a cycle of cold water descending deep underground, being heated by hot rock or magma, expanding, and being driven back towards the surface.

SPRING GENERATION

Volcanic hot springs occur when surface water trickles down through the crust until it comes into contact with the rocks surrounding a magma chamber, or the magma itself. As the water warms, typically close to boiling point, it becomes less dense, and rises up through fissures and chambers in the rock until it reaches the surface, where it forms a pool of hot water. Often, the water temperature in such a pool or spring is very high – many springs have temperatures in the range from 70°C (158°F) to as high as 97°C (206°F).

FLOW RATE AND MINERAL CONTENT

Volcanic hot springs usually produce an uninterrupted flow of hot water every second at an average temperature of 97°C (206°F). They vary from insignificant seeps to strong plumes, such as the hot spring at Deildartunguhver, Iceland, which flows at a rate of 180 litres (50 gallons) every second. During its underground journey, the hot water dissolves minerals out of the rock. As well as colouring some springs, minerals often precipitate out when the water cools at the surface, producing hard deposits that can develop into spectacular formations, such as the travertines at Mammoth Hot Springs in Wyoming, USA.

THERAPEUTIC POTENTIAL



Some volcanic hot springs contain warm rather than hot water, making them safe to bathe in. The bathing pool in the Blue Lagoon spa in Iceland uses water processed by the nearby geothermal plant, with water temperature averaging 37 to 39°C (98 to 102°F). Bathing in the mineral-enriched waters of a hot spring is reputed to have therapeutic value, for example, in alleviating some skin ailments, as well as psychological benefits.



BOILING LAKE, DOMINICA
This scaldingly hot body of water, on a Caribbean island, is one of the world's largest hot springs. Its surface is permanently enveloped in a cloud of steam.



CHAMPAGNE POOL, NEW ZEALAND
Formed 900 years ago in the Wai-o-tapu geothermal area, the Champagne Pool contains salts of arsenic and antimony, which give it a colourful appearance.



DALLOL HOT SPRINGS, ETHIOPIA
Located in the hot, highly volcanic Danakil Depression, these springs are notable for the various strangely shaped mineral deposits found around them.



RIOT OF COLOURS
Hot springs may be brightly coloured due to the presence of microbes. Differently coloured microbes with different temperature preferences can lead to a spectrum of colours in one pool, as seen here at Grand Prismatic Spring in Yellowstone Park, USA.

FUMAROLES

Found in many of the world's volcanic regions, fumaroles are openings in the planet's crust that emit steam and a variety of volcanic gases, such as carbon dioxide, sulphur dioxide, and hydrogen sulphide. They often make loud hissing noises as the steam and gases escape. Many fumaroles are extremely foul smelling.

CHARACTERISTICS

Fumaroles are similar to hot springs (see pp.110–111). However, unlike in hot springs, the water in fumaroles gets heated to such a high temperature that it boils into steam before reaching the surface. The main source of the steam emitted by fumaroles is groundwater heated by magma lying relatively close to the surface. Other gases, such as carbon dioxide, sulphur dioxide, hydrogen sulphide, and smaller amounts of water, are released from the magma. Fumaroles are often present on active volcanoes during periods of relative quiet between eruptions. They may last for decades or centuries if they are above a persistent heat source, or disappear within weeks if they occur atop a fresh volcanic deposit that cools quickly.



ANDEAN FUMAROLE FIELD
The Sol de Mañana fumarole field in Bolivia is a wilderness of steam and sulphur deposits. Located at an altitude of 4,870m (15,975ft) in the Andes, near Bolivia's border with Chile, it extends over 10 sq km (4 sq miles) and contains lakes of boiling mud.





SULPHUROUS FUMAROLES

A fumarole that emits a lot of hydrogen sulphide, which smells of rotten eggs, or pungent-smelling sulphur dioxide, is called a solfatara. Hydrogen sulphide often reacts with other gases to make sulphur, which is deposited on the ground as yellow crystals. The steam and sulphurous gases also combine to make weak sulphuric acid. In some locations, this dissolves nearby rocks into a mass of hot mud and may also be a health hazard for downwind communities.

MOUNT ASAHI-DAKE, JAPAN
Numerous snow-melting fumaroles punctuate the sides of the stratovolcano Asahi-dake, on the island of Hokkaido, Japan. They create a remarkable sight in winter when the slopes are used as a skiing area.

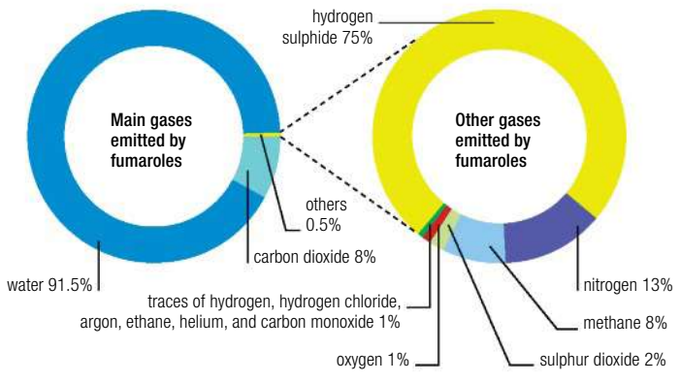




DALLOL FUMAROLES AND ACID POND
The Dallol region of Ethiopia, one of the lowest and hottest spots on the Earth, consists of many hot springs, fumaroles – seen here at the top of conical mounds – and sulphur deposits. The liquid on the ground is weak sulphuric acid.

FUMAROLE GASES

The diagram shows the breakdown of gases given off by fumaroles in one large study (in Taiwan) and is considered fairly typical. While water and carbon dioxide predominate, another major component – the poisonous gas hydrogen sulphide – is what gives most fumaroles their unpleasant smell.







SULPHUR CRYSTALS

GRAN CRATERE, VULCANO
Extensive sulphur deposits cover the rim of the Gran Cratere ("big crater") on the small volcanic island of Vulcano, north of Sicily, Italy. Numerous active fumaroles exist within the crater, and visitors are advised to avoid breathing in the foul-smelling, poisonous gases they give off.

GEYSERS

Geysers are extraordinary natural fountains that intermittently shoot boiling-hot water and steam into the air in violent eruptions. They form under rare conditions and exist in only a few locations worldwide.

ACTIVITY AND TYPES

Like hot springs (see pp.110–111), geysers result from increased heat flow from Earth's interior meeting fluids in permeable or fractured rocks. However, there is a crucial difference between the two. In a hot spring, water flows freely from below the ground, so no pressure builds up. A geyser, in contrast, has a narrow opening near the top of its plumbing system that restricts movement of water. As a result, pressure can intermittently build up, aided by the presence of geyserite, a pressure-sealing mineral that lines all of a geyser's underground chambers and channels. It is a form of silica that precipitates at hot springs and geysers.

As pressure builds inside a geyser's subterranean chambers, the water is unable to change into steam, even though the temperature of the water may rise to 250°C (480°F). Eventually, the high pressure blasts water out from the constricted opening. As this happens, pressure falls further down in the plumbing system, allowing some of the hot water to flash into steam, which then rapidly expands. This sustains the eruption, which continues until pressure in the geyser has dropped close to zero. The whole cycle then starts again. There are two main types of geyser: cone and fountain. In a cone geyser, geyserite forms a cone-shaped nozzle at the surface, which directs the flow of water. By contrast, the surface opening of a fountain-type geyser is a crater filled with water, so its eruptions are more diffuse. Geysers are highly variable in their behaviour – some erupt frequently and regularly, others do not. While most eruptions last for only a few minutes, some may persist for hours.

> "THAT WHICH THE FOUNTAIN SENDS FORTH RETURNS AGAIN TO THE FOUNTAIN."
>
> **HENRY WADSWORTH LONGFELLOW**, AMERICAN POET, REFERRING TO CYCLICAL PHENOMENA



CASTLE GEYSER
This cone geyser in the Yellowstone National Park, USA, erupts every 10 to 12 hours, sending a fountain to a height of 27m (89ft) for 20 minutes. Carbon dating suggests that it is 5,000 to 15,000 years old.

540
The approximate number of active geysers in Yellowstone, which represents about half the global total. Most other geysers are found either in New Zealand's North Island, in northern Chile, Iceland, or in a small area in Kamchatka in eastern Russia.

WORLD'S TALLEST GEYSERS

NAME	LOCATION	HEIGHT (MAX)	ERUPTION CYCLE
Steamboat	Yellowstone, USA	90m (295ft)	Irregular
Giant	Yellowstone, USA	75m (245ft)	Irregular
Splendid	Yellowstone, USA	75m (245ft)	Irregular
Geysir	Iceland	70m (230ft)	Irregular
Great Fountain	Yellowstone, USA	67m (220ft)	9–15 hours
Beehive	Yellowstone, USA	60m (200ft)	8–24 hours
Grand	Yellowstone, USA	60m (200ft)	7–15 hours
Giantess	Yellowstone, USA	60m (200ft)	Irregular



STROKKUR

One of Iceland's most famous spectacles, Strokkur is a fountain geyser that erupts every 4 to 8 minutes, sending steam and water to a maximum height of 30m (98ft). Eruptions were first reported in 1789, after an earthquake.

MUD VOLCANOES

The less-famous cousins of ordinary magmatic (lava- and ash-erupting) volcanoes, mud volcanoes are channels through which large amounts of pressurized gas, mud, and salty water are expelled from deep underground onto Earth's surface. Once dry, the mud builds up into cones that can be up to several hundred metres high.

CAUSES AND DISTRIBUTION

Mud volcanoes are caused by pressure building up underground, in regions where gas and water are trapped. As the gas and water are driven up towards the surface through lines of weakness in the crust, they soften some of the rock layers they encounter, turning these into mud. Pressure exerted by gas deposits deep in the crust can be a major precipitating factor, so many mud volcanoes occur near gas fields. They may also develop near tectonic plate boundaries and fault lines. More than 1,000 mud volcanoes have been identified on land and in shallow water – in eastern Azerbaijan, Romania, Venezuela, and elsewhere. They also exist underwater – about 10,000 are thought to be scattered across continental shelf areas and the deep sea floor.



GEOTHERMAL VOLCANO
Although a separate phenomenon from the mud pools that are often seen in geothermal areas, mud volcanoes sometimes occur in such areas, as here in Rotorua, New Zealand.

BARREN LANDSCAPE
Where mud volcanoes occur, they create a strange lunar-like landscape. Vegetation is normally sparse or absent, because most plants cannot tolerate the amount of salt deposited in the soil along with the mud.





SHALLOW MUD VOLCANO
This unusual, small mud volcano with gently sloping, mineral-stained sides, formed in Glen Canyon, Utah, USA. It erupts watery mud from its vent and has developed a shallow summit crater.

MUD CONES
In Azerbaijan, southwest Asia, mud volcanoes commonly form lines of small cones. These emit cold mud, water, and gas almost continually from a deep underground reservoir.





SMALLER SCALE
This mud volcano in Berca, Romania, has the same conical shape as a typical magmatic volcano, but is much smaller in scale.

CAULDRON OF GASES
At Yellowstone National Park, USA, is a steam-belching, mud-filled hole in the ground that is referred to as a mud volcano. However, it is really a fumarole (see pp.112–113) – an opening through which steam and other gases escape.



ERUPTION CHARACTERISTICS

The mud spewed out by a mud volcano varies in its temperature and viscosity (runniness), depending on the volcano. It is usually cold, since it comes from the crust and not the mantle, but some volcanoes release warm mud. Where the underground pressure causing a volcano is especially high, it may break rock formations, throwing out chunks of rock with the mud. Mud volcanoes also emit large amounts of gases, mainly hydrocarbons such as methane. A large methane plume can ignite at the vent of a mud volcano. In Azerbaijan, mud volcanoes have erupted explosively, hurling flames from burning methane hundreds of metres into the air, and depositing tonnes of mud on surrounding areas.

THE LUSI DISASTER

In May 2006, one of the largest mud volcano eruptions ever recorded was triggered in the Sidoarjo region of eastern Java, Indonesia. The eruption, called Lumpur Sidoarjo (***lumpur*** is Indonesian for "mud"), or Lusi, is continuing and is expected to do so until about the year 2040. It has already flooded an area of about 10 sq km (4 sq miles) with mud and forced more than 40,000 people out of their homes. In addition, 13 people were killed in November 2006 when subsidence near the eruption site ruptured a gas pipeline and caused an explosion. Faulty procedures during the drilling of a nearby gas well have been blamed for triggering the disaster. Experts believe that the well accidentally punched into an aquifer deep below the surface, allowing hot water under high pressure to escape, rise, and mix with a layer of volcanic ash, causing the blowout. But the company that drilled the well claims an earthquake was the cause. Legal proceedings connected to the Lusi disaster continue.

29 MAY 2006–PRESENT

Location	East Java, Indonesia
Type	Mud volcano
Fatalities	13

40,000

THE NUMBER OF PEOPLE DISPLACED

68

The number of Olympic-sized swimming pools that the mud flow could have filled each day, during peak flow rates. It reached about 7,000 cu m (250,000 cu ft) per hour at times during the first 18 months after the eruption started.

CATASTROPHE UNFOLDS





1 BLOW OUT
A day after a new gas borehole was drilled nearby, plumes of steam and hot sulphurous mud suddenly appeared from a ground fissure near the village of Porong.



LARGEST MUD VOLCANO
A plume of steam rises from one of the mud volcano's vents, which is essentially a simple circular hole in the ground. Efforts to plug the flow have only resulted in more vents appearing that continue to maintain the mud flow.

DISASTER RESPONSE

So far, all efforts to stem the mud flow have failed, though its flow rate has diminished naturally. Huge dikes were built to surround and contain the affected area, but there have been occasional breakouts from these. Also, there are major concerns that the whole area inundated will subside, perhaps as much as 150m (500ft), due to the ever-increasing weight of the mud.



Pumping the mud
Some efforts are being made to pump the mud out of the flooded area into a nearby river. But as the river carries the mud down to the coast and deposits it as sediment, there are concerns about the wider impact on coastal ecosystems.



Plugging holes
To slow the mud flow, engineers tried dropping hundreds of huge concrete balls – each weighing 40kg (88lb) and linked together by chains – into the largest vent. However, it had a barely noticeable effect.



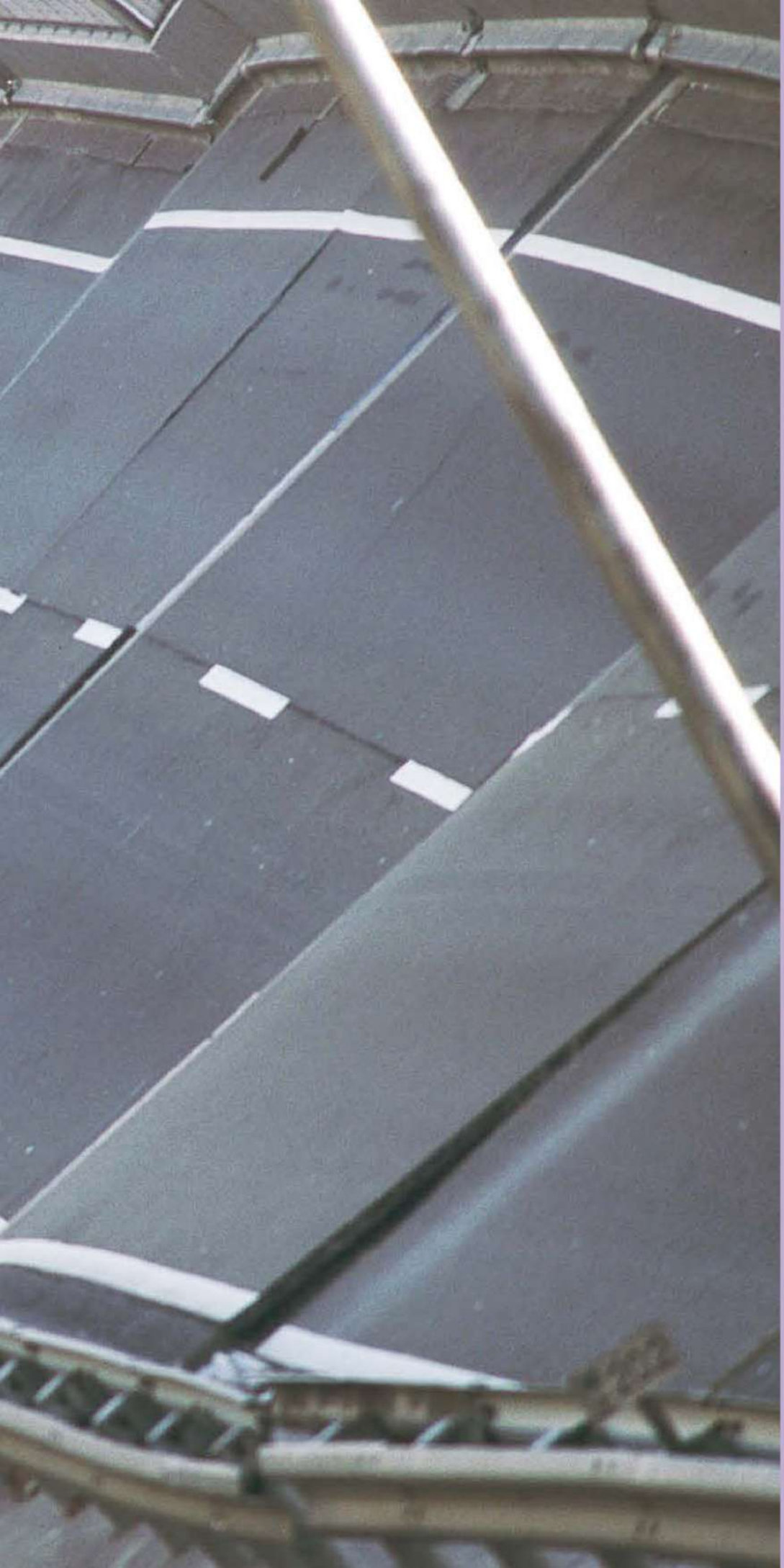
2 SLUDGE COVER
Within two years, a dozen nearby villages, containing many thousands of homes, had been submerged in mud to a depth of several metres.

> "...IT WILL TAKE 26 YEARS FOR THE ERUPTION TO DROP TO A MANAGEABLE LEVEL AND FOR LUSI TO TURN INTO A SLOW-BUBBLING VOLCANO."
>
> **RICHARD DAVIES**, DIRECTOR OF DURHAM ENERGY INSTITUTE, UK, 2011



3 LAND DEVOURED
This false colour near-infrared satellite image from November 2008 clearly shows the roughly rectangular area created by the containment dikes built to hold the grey mud back. The surrounding vegetation appears red.





EARTHQUAKES

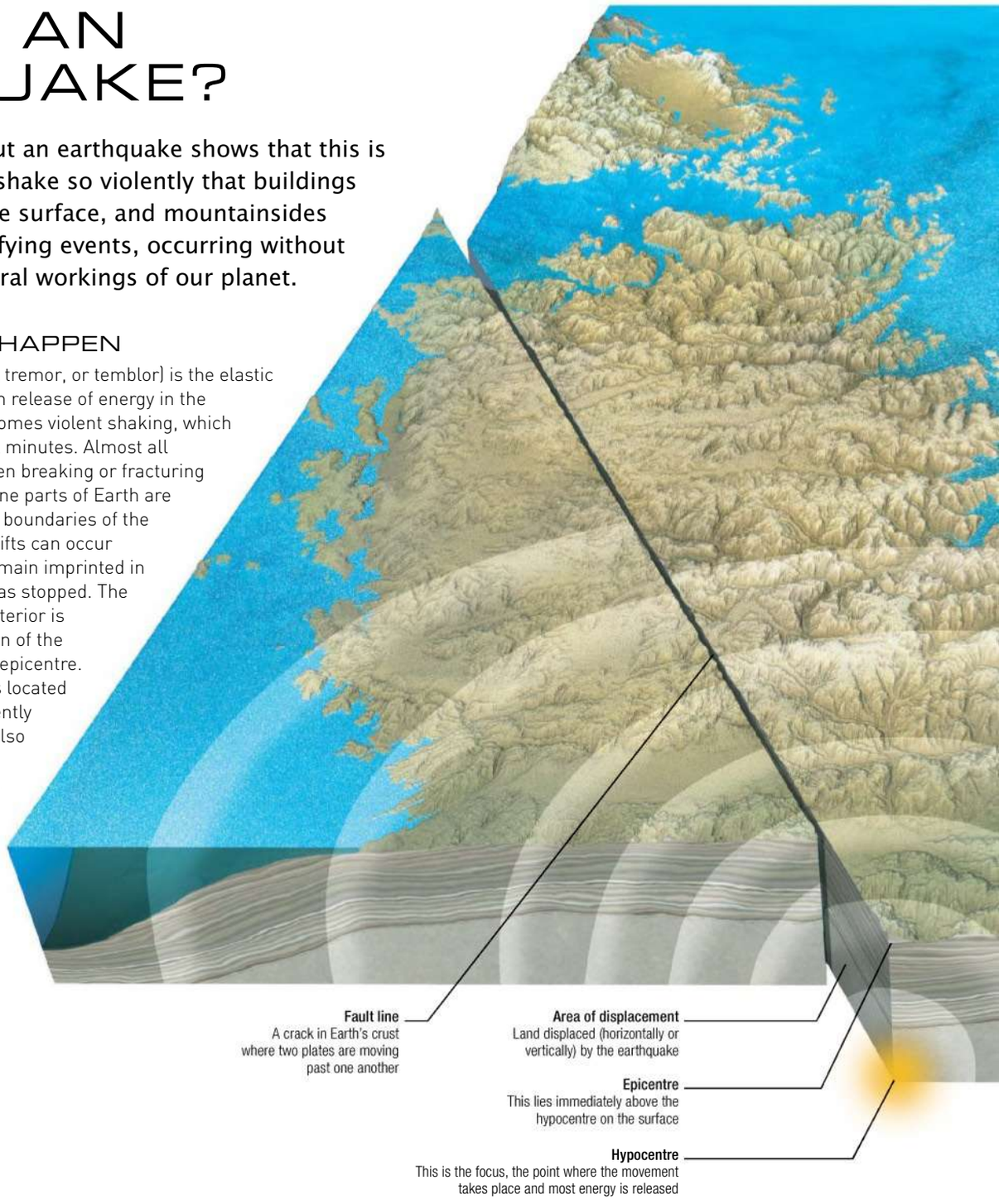
<< Earthquake damage
The magnitude-6.9 earthquake that struck Kobe, Japan, in 1995 caused several portions of an elevated highway to collapse.

WHAT IS AN EARTHQUAKE?

The ground may feel solid but an earthquake shows that this is not the case – the Earth can shake so violently that buildings collapse, rents open up in the surface, and mountainsides tumble down. Yet these terrifying events, occurring without warning, are part of the natural workings of our planet.

WHY EARTHQUAKES HAPPEN

An earthquake (also known as a quake, tremor, or temblor) is the elastic vibration of rocks caused by the sudden release of energy in the Earth's interior. At the surface this becomes violent shaking, which may last from a few seconds to several minutes. Almost all earthquakes are triggered by the sudden breaking or fracturing of rocks, and the most earthquake-prone parts of Earth are the tectonically active regions near the boundaries of the tectonic plates. Profound geological shifts can occur during an earthquake, changes that remain imprinted in the landscape long after the shaking has stopped. The location of the earthquake in Earth's interior is called the hypocentre and the projection of the hypocentre at the surface is called the epicentre. When a large earthquake's epicentre is located offshore, the seabed may move sufficiently to cause a tsunami. Earthquakes can also trigger landslides, and occasionally volcanic activity. But the consequences to man-made structures near the epicentre can be devastating, leading to huge loss of life.



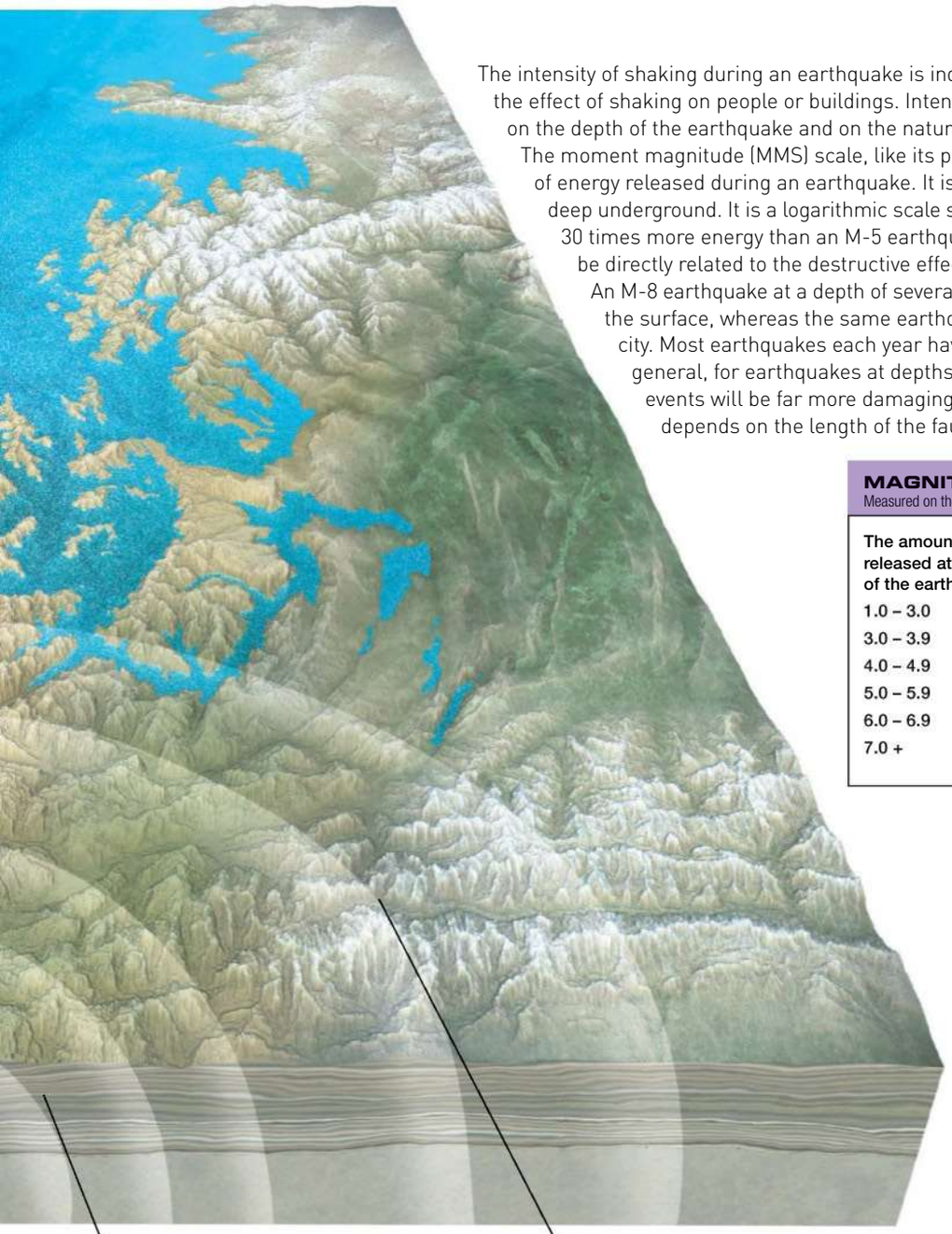
EARTHQUAKE FAULT LINE
Earthquakes occur below fault lines that cut through the landscape, most commonly near tectonic plate boundaries. Since the plates are moving in different directions, stress builds up in the rock. Movement begins at the epicentre, deep within the crust. Waves of energy radiate outwards, shaking the ground above. Blocks of land are displaced either horizontally or vertically.



STRUCTURAL DAMAGE
The ground accelerations caused by shaking during even a moderate earthquake can easily exceed gravity and are enough to topple free-standing structures. Buildings and other structures that lack internal bracing, or with poorly supported roofs or walls, will collapse.



TSUNAMI
If the seabed is uplifted or dropped suddenly as a consequence of ground movements, then large volumes of water will be displaced, creating a tsunami, a series of waves, that travels at more than 700kph (400mph) across the ocean. Waves can be more than 10m (33ft) high.



Tectonic plates
Huge blocks of crust slide past or over each other. These movements lead to earthquakes

Seismic waves
Waves of energy radiate out from the epicentre, on the surface as well as underground

The intensity of shaking during an earthquake is indicated on the modified Mercalli scale, which measures the effect of shaking on people or buildings. Intensity is measured at a point at the surface and depends on the depth of the earthquake and on the nature of the ground – hard rock shakes less than soft ground. The moment magnitude (MMS) scale, like its predecessor the Richter scale, is a measure of the amount of energy released during an earthquake. It is an estimate of the energy at the source, which may be deep underground. It is a logarithmic scale so, for example, an M-6 earthquake releases roughly 30 times more energy than an M-5 earthquake. However, the moment magnitude scale cannot be directly related to the destructive effects of the quake, because this depends on the location. An M-8 earthquake at a depth of several hundred kilometres is unlikely to do much damage at the surface, whereas the same earthquake at a depth of only a few kilometres could destroy a city. Most earthquakes each year have a small moment magnitude, with fewer larger ones. In general, for earthquakes at depths of less than 50km (30 miles), large moment magnitude events will be far more damaging than smaller ones, but the destructive power also depends on the length of the fault that breaks.

MAGNITUDE Measured on the moment magnitude scale	**INTENSITY** Typical maximum on the modified Mercalli scale
The amount of energy released at the source of the earthquake	**The intensity or strength of the shaking measured by the effect on people and buildings**
1.0 – 3.0	**I** (not felt)
3.0 – 3.9	**II – III** (felt on upper floors of buildings)
4.0 – 4.9	**IV – V** (rocking motion felt by most)
5.0 – 5.9	**VI – VII** (some damage to buildings)
6.0 – 6.9	**VII – IX** (moderate to considerable damage)
7.0 +	**VIII +** (slight damage to total devastation)



SHAKING
One of the most obvious effects of the waves of seismic energy released during an earthquake is the shaking experienced at Earth's surface. One of the safest places to be during an earthquake is braced in a doorframe or under a table.



LANDSLIDES
The most earthquake-prone parts of Earth also tend to be mountainous. The shaking during an earthquake can destabilize hill slopes, causing rock falls and landslides (see pp.156–157). Landslides can be one of the greatest causes of death in an earthquake.



FIRES
Fires are not a direct consequence of earthquakes, however, when an earthquake severely shakes the ground beneath a city, electricity cables, gas pipes, and oil installations can be damaged or broken. Electrical faults or overheating can lead to explosions and fires.

EARTHQUAKE ZONES

10 LARGEST EARTHQUAKES SINCE 1950

1 VALDIVIA
Country: Chile
Date: 1960
Magnitude: M–9.5

2 PRINCE WILLIAM SOUND
Country: Alaska, USA
Date: 1964
Magnitude: M–9.2

3 INDIAN OCEAN
Country: Off the coast of Sumatra
Date: 2004
Magnitude: M–9.1

4 KAMCHATKA
Country: Russia
Date: 1952
Magnitude: M–9.0

5 TOHOKU
Country: Japan
Date: 2011
Magnitude: M–9.0

6 MAULE
Country: Chile
Date: 2010
Magnitude: M–8.8

7 RAT ISLANDS
Country: Alaska, USA
Date: 1965
Magnitude: M–8.7

8 ASSAM
Country: India
Date: 1950
Magnitude: M–8.6

9 ANDREANOF ISLANDS
Country: Alaska, USA
Date: 1957
Magnitude: M–8.6

10 SUMATRA
Country: Indonesia
Date: 2005
Magnitude: M–8.5

10 DEADLIEST EARTHQUAKES SINCE 1900

11 HAITI
Country: Haiti
Date: 2010
Deaths: 316,000

12 TANGSHAN
Country: China
Date: 1976
Deaths: 242,769

13 INDIAN OCEAN
Country: Off the coast of Sumatra
Date: 2004
Deaths: 227,898

14 GANSU
Country: China
Date: 1920
Deaths: 200,000

15 GREAT KANTO
Country: Japan
Date: 1923
Deaths: 142,800

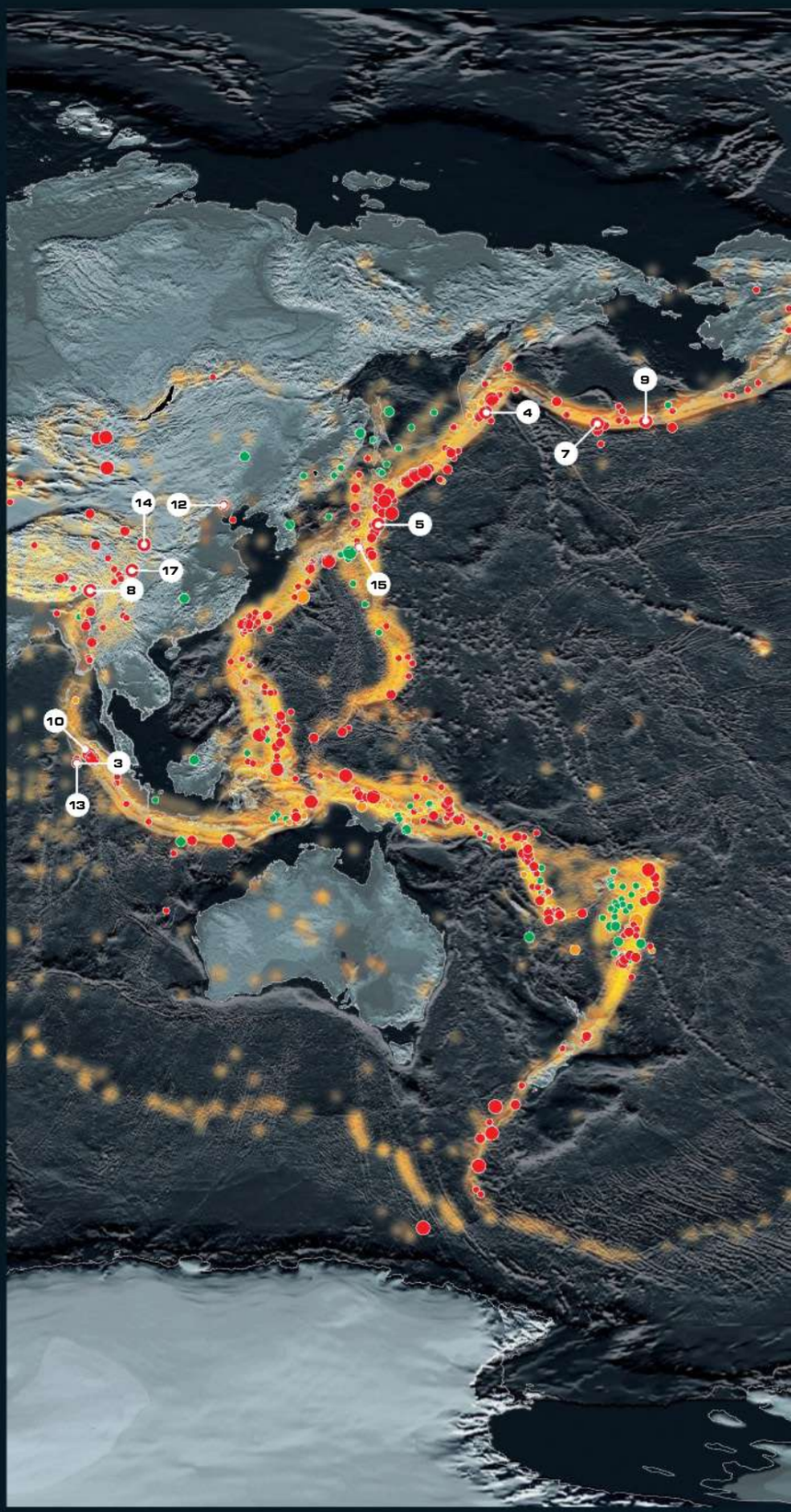
16 ASHGABAT
Country: Turkmenistan
Date: 1948
Deaths: 110,000

17 SICHUAN
Country: China
Date: 2008
Deaths: 87,587

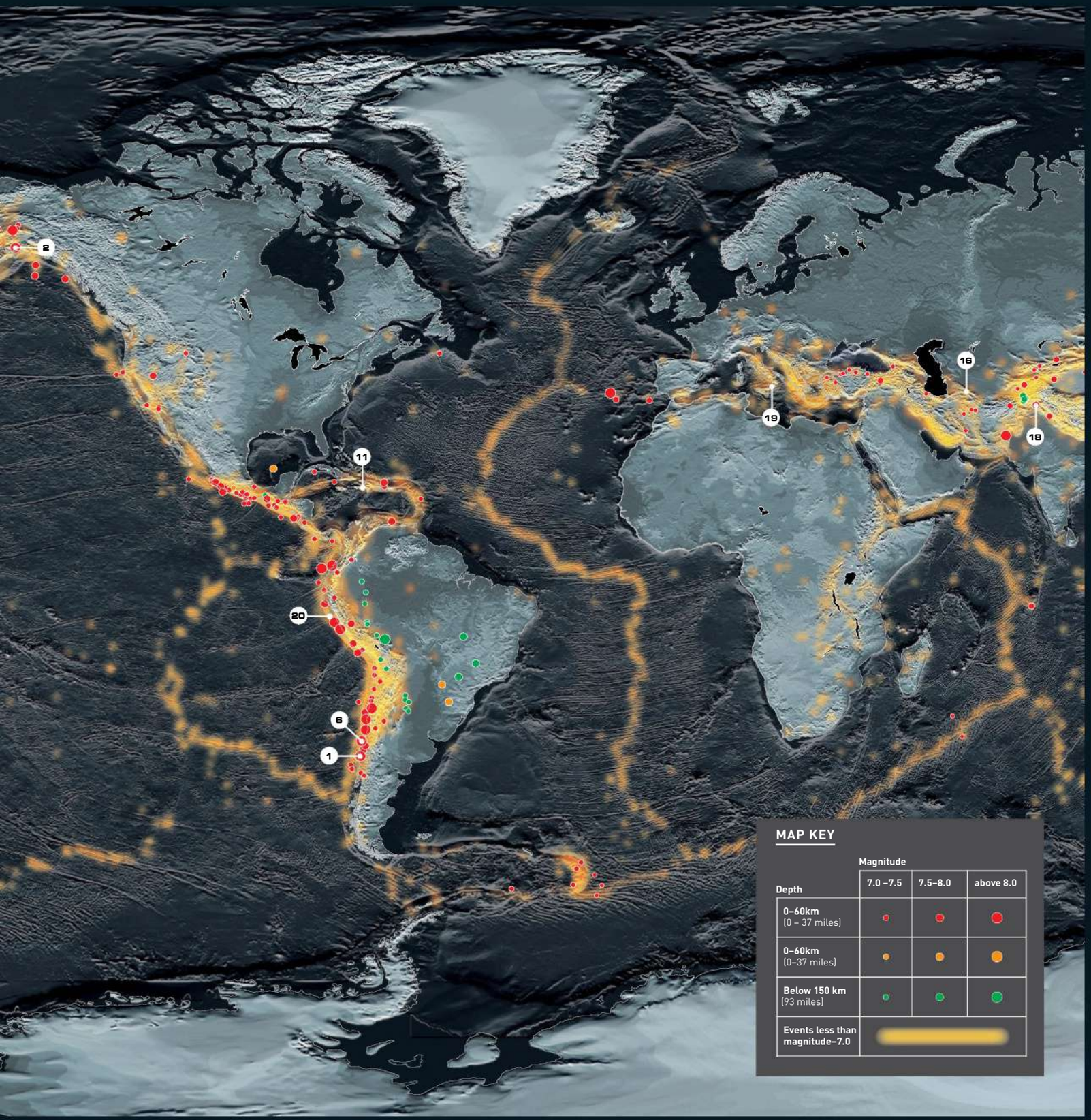
18 AZAD, KASHMIR
Country: Pakistan
Date: 2005
Deaths: 86,000

19 MESSINA
Country: Italy
Date: 1908
Deaths: 72,000

20 CHIMBOTE
Country: Peru
Date: 1970
Deaths: 70,000



One of the great geological discoveries about our planet is that it is alive with earthquakes. Almost all of these earthquakes occur in relatively narrow zones along the edges of the tectonic plates. Most big earthquakes occur around the Pacific margin, in the notorious “Ring of Fire”.

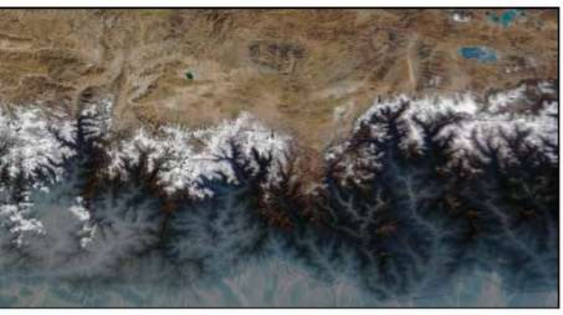


CAUSES OF EARTHQUAKES

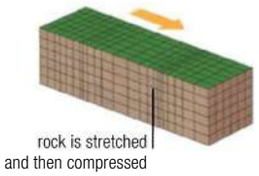
Along the boundaries of the tectonic plates, rocks are squeezed and stretched like a spring by the huge forces inside Earth. Nearer the surface, rocks are sufficiently cold and strong that they eventually break along faults. If this occurs suddenly, the rocks snap, generating the violent vibrations of an earthquake.

FAULT LINES

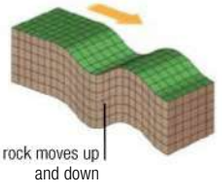
Geologists have long observed that Earth's crust is intensely broken and fractured, cut through by fault lines. Some of these fault lines extend for hundreds or even thousands of kilometres, traversing great tracts of the continents. Others are only visible under a microscope. The link between movement along faults and earthquakes was realized by geologists in the late 19th century, but it was not until the great 1906 San Francisco earthquake that scientists began to study the connection closely. Man-made structures, including railway lines and roads, were offset across the fault line during the earthquake.



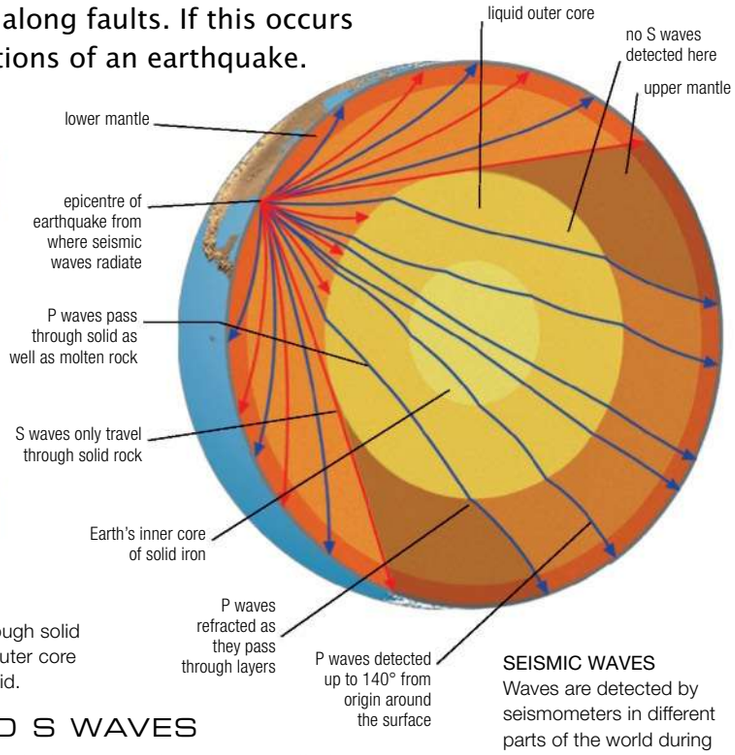
HIMALAYAN MOUNTAINS
The Himalayas lie above a giant, gently inclined fault line, which ruptures every few hundred years during earthquakes. Movement on this fault is pushing up the mountains.



P WAVES
P waves pass through any material including liquids such as molten rock.



S WAVES
S waves can only move through solid rock. Their absence in the outer core is key evidence that it is liquid.

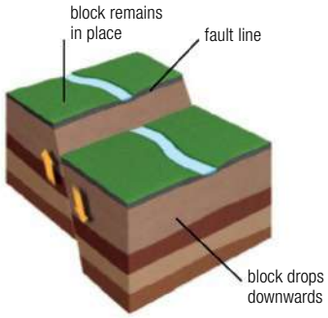


SEISMIC WAVES
Waves are detected by seismometers in different parts of the world during an earthquake, and are used by seismologists to unravel the sequence of events, including the direction and amount of slip on the earthquake-generating fault. The time delay between the P and S waves can be used to locate the earthquake.

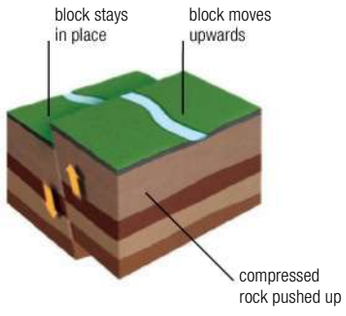
P WAVES AND S WAVES

The vibrations that occur during an earthquake have distinct patterns. Some travel right through Earth's interior, and are called elastic body waves with two distinct types of motion. P waves (primary), or compressional waves, are the first to arrive at a seismometer, travelling through the crust at about 6km per second (3.5 miles per second). They have a back-and-forth motion, like a vibrating spring, and are identical to sound waves, but at too low a frequency to be heard by the human ear. S waves (secondary), or shear waves, have a distinctive snake-like motion and travel relatively slowly – typically at a speed of about 4km per second (2.5 miles per second) in the crust – arriving after the P waves.

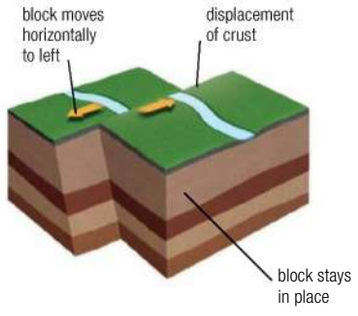
FAULT LINES AND LANDSCAPES



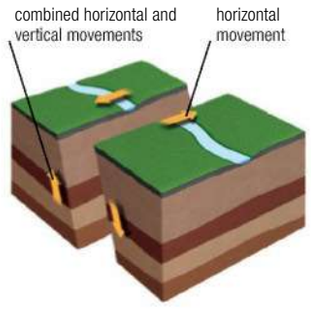
NORMAL FAULT
When rocks are stretched horizontally, they break along normal faults. Here, the overlying rocks slide down the fault and away from the underlying rocks.



REVERSE FAULT
The overlying rocks slide upwards giving rise to uplifted regions or mountain ranges. Faults inclined at less than 45° are referred to as thrust faults.



STRIKE-SLIP FAULT
Two sides of the fault slide past each other horizontally. If this is to the right, it is referred to as right-lateral. If it is to the left, it is left-lateral.



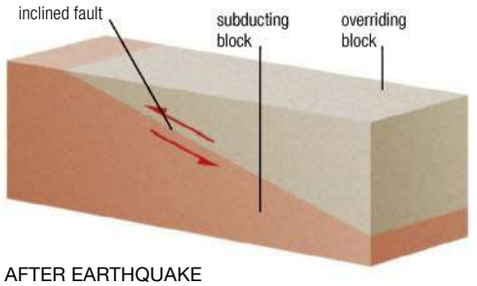
OBLIQUE-SLIP FAULT
When a strike-slip fault is combined with either extension or compression, the blocks can slide diagonally producing an oblique-slip fault.



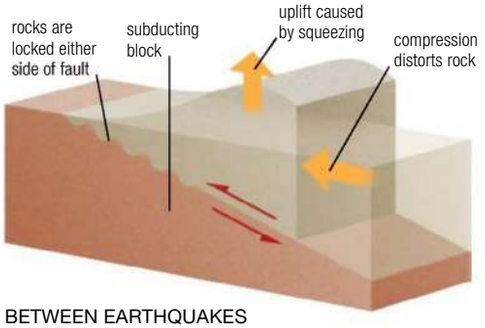
OFFSET RAILWAY LINES
Elastic rebound either side of the fault buckled these railway lines after the 1987 magnitude-6.3 Edgecombe quake in New Zealand.

ELASTIC REBOUND

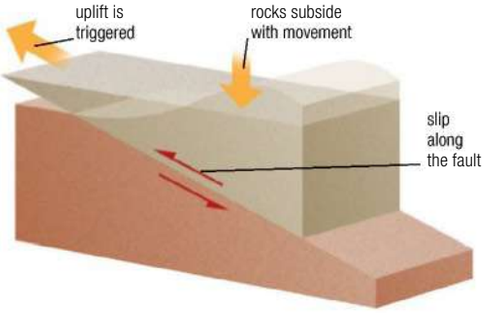
US geologist Harry Fielding Reid studied the 1906 San Francisco earthquake and suggested that the rocks were behaving rather like a piece of elastic. Before the earthquake there was no movement on the fault itself, but the surrounding rocks were being slowly distorted. Eventually, this distortion exceeded the limit that rocks could undergo and they snapped, breaking along the fault. It was this sudden snapping, or "elastic rebound", that generated the violent shaking during the earthquake. Movement on the fault during the 1906 earthquake was strike-slip (see pp.144–145). However, this pattern of elastic distortion, then sudden breaking when an earthquake occurs, can be observed on all types of faults, resulting in the characteristic ground motions that geologists call the "earthquake cycle".



AFTER EARTHQUAKE
After a sudden slip along the fault, the earthquake cycle soon begins again as the rocks and land surface settle into a new arrangement.



BETWEEN EARTHQUAKES
The motion of the tectonic plates causes stress to build up. There is no movement on the fault, but the rocks are distorted as stress accumulates.



The accumulated strain that has built along the fault eventually overcomes the strength of the rock and unlocks it. The rock plates then spring back, releasing the displacement and producing an earthquake.

HAITI 2010

On Tuesday 12 January 2010, at 16:53 local time, a magnitude–7.0 earthquake struck close to Port-au-Prince, the capital of Haiti, in the Caribbean Sea. The earthquake was felt as far afield as parts of the Bahamas, Puerto Rico, and the US Virgin Islands, and even in southern Florida, northern Colombia, and northwestern Venezuela. It occurred in a geologically active region at the boundary between the Caribbean and the North American plates, where the Caribbean Plate is moving about 20mm (0.8in) per year relative to North America, mainly along left-lateral strike-slip faults. However, the main shock did not produce any observable surface displacement on the main fault lines in this region, including the nearby Enriquillo-Plaintain Garden Fault, but rather on previously undetected faults. The earthquake was followed by as many as 52 aftershocks measured at magnitude–4.5 or above between 12–24 January.



12 JANUARY 2010	
Location	Haiti
Type	Strike-slip fault
Magnitude	7.0

222,570

NUMBER OF PEOPLE REPORTED DEAD



INTERNATIONAL RESCUE
Search-and-rescue teams from all over the world, including the USA, Britain, Japan, and New Zealand, came to the aid of the Haitians.



THE PRESIDENTIAL PALACE BEFORE AND AFTER
A significant proportion of the city of Port-au-Prince was destroyed in the earthquake, including the Presidential Palace, the National Assembly, and Port-au-Prince cathedral. Haiti is a poor country, and inadequate design codes for earthquake-proof buildings led to much of the damage.

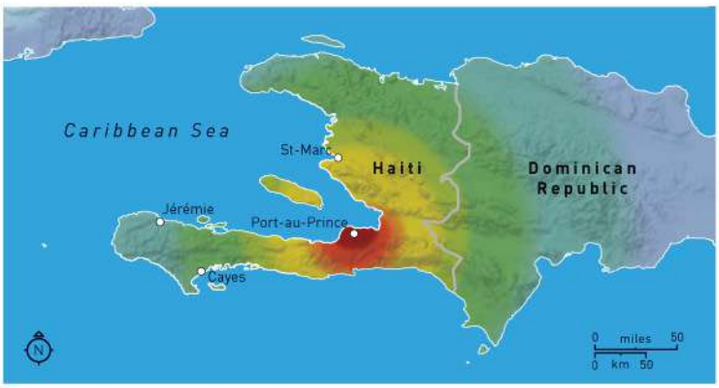
AFTER THE QUAKE
A shortage of clean drinking water was a major problem for the population of Port-au-Prince and diseases, such as diarrhoea spread easily. Aid organisations made water-filtration systems a priority.



IMPACT AND CASUALTIES

According to official estimates, 222,570 people were killed, 300,000 injured, 1.3 million displaced, 97,294 houses destroyed, and 188,383 houses damaged in the Port-au-Prince area of southern Haiti. This total includes at least four people killed by a local tsunami. The earthquake destroyed the main infrastructure in Port-au-Prince – a town of nearly 750,000 people – especially the water and sewerage systems. Most of the population were displaced into temporary accommodation where there was poor sanitation and little clean drinking water, leading to the spread of cholera and dysentery.

> "WE HAD A LOT OF HOUSES DESTROYED, A LOT OF PEOPLE DEAD... A LOT OF PROBLEMS."
>
> **JEAN**



Percieved shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Potential damage	None	None	None	Very light	Light	Moderate	Moderate heavy	Heavy	Very heavy
Intensity	1	2–3	4	5	6	7	8	9	10+

HAITI SHAKE MAP

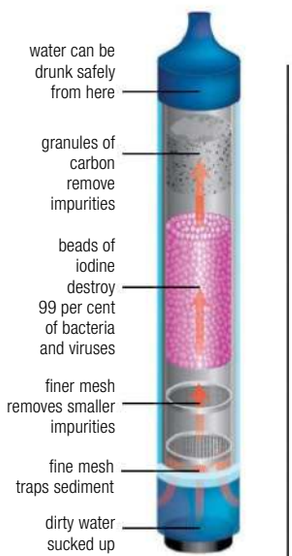
This colour-coded map shows the intensity of the shaking experienced, from red (most intense) to grey (weak). The most intense shaking is close to the epicentre, where a fault ruptured at depth. However, the intensity of shaking was also determined by the nature of the local sediments beneath Port-au-Prince.

WATER PURIFICATION

Damage to the water and sewage systems in Port-au-Prince led to wells and water mains becoming contaminated with dirty water and sewage, which eventually became a major source of waterborne diseases such as dysentery and cholera. To deal with this problem, aid teams distributed water purification kits. Designed for personal use, a simple tube device, called a LifeStraw, consists of a series of filters: some are fabric and some chemical. Mesh filters trap dirt and sediment and an iodine layer destroys most bacteria and viruses, then active carbon granules purify water using a process called adsorption. This also helps to remove the unpleasant taste of the iodine.

LifeStraw

This specially designed tube of filters can save lives when it is used as a straw to safely drink contaminated water.



MOVEMENTS AND FAULTS

Earthquakes are an expression of a more profound process – the long-term shifting of rocks and the landscape caused by the motion of tectonic plates. Geologists measure and monitor these movements, either directly using accurate positioning systems, or by studying geological changes in the landscape.

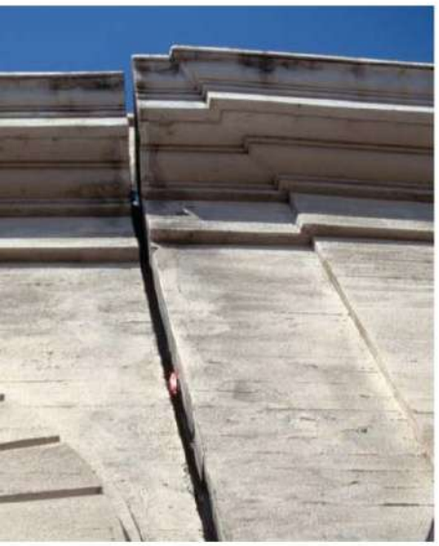
LATERAL AND VERTICAL MOVEMENTS

The permanent changes in the landscape that occur during an earthquake extend over a wide region, up to hundreds of kilometres from the epicentre. Close to the epicentre, if the quake is fairly shallow, there will be an abrupt break in the ground surface, revealing a fault that has broken during the earthquake. In the largest earthquakes (magnitude-8 and above on the Moment Magnitude scale), displacements on the fault up to nearly 20m (66ft) have been observed, though a displacement up to a few metres is more typical of an earthquake of magnitude-6 and above. These displacements may be both vertical and horizontal shifts of the land surface, which over a span of geological time, shape our Earth.

2.5–15cm
(1–6in) The range of distance that each tectonic plate can move relative to Earth's interior each year.



VERTICAL MOVEMENT
Along the Hanning Bay Fault on Montague Island in Prince William Sound, Alaska, USA, vertical movement of about 4m (13ft) created this new scarp in the landscape during the 1964 magnitude-9.2 earthquake. Repeated over many earthquakes, vertical motion like this can create a mountain range.



SHIFTING STADIUM
The exterior walls of Berkeley's Memorial Football Stadium, California, USA, are slightly offset. The Hayward Fault runs across the field, and the two halves of the stadium have shifted since it was constructed.

EARTHQUAKE FAULT CREEP

Not all faults in the landscape are inactive between earthquakes. Though tremors may not be felt at the surface, the fault may still be moving. Several fault lines in California and Turkey have been observed to "creep", or make slight but continuous movements. In some cases, these creeping motions seem to decrease with time, and are likely to represent continued longer term readjustments of the fault after an earthquake. The Hayward Fault in California is still moving, offsetting buildings, drains, and roads that cross its path. In Turkey, part of the North Anatolian Fault, near Ismit Pasha, was observed to creep in the 1970s and 1980s, continually distorting a railway line that crossed its path. But at depths of a few tens of kilometres, where the rocks are sufficiently hot and weak, all faults undergo continuous creep along aseismic, ductile, shear zones. The earthquake-generating part of the fault is confined to the colder and stronger rock at shallower depths, where the movement of the fault occurs in a series of earthquake-triggering jerks. Between earthquakes, the motion at this depth is absorbed by distortion of the rocks over a wide area.

> "HUGE AMOUNTS OF STRESS BUILD UP. WHEN THE STRESS IS TOO GREAT, THE ROCKS FORCE APART LIKE A... SPRING."
>
> **PROFESSOR GEOFFREY KING**, INSTITUT DE PHYSIQUE DE GLOBE



KASHIWAZAKI JAPAN
This right-lateral shift across a field in Kashiwazaki, Japan, indicates a fault line that appeared following the earthquake in Kobe in 1995.

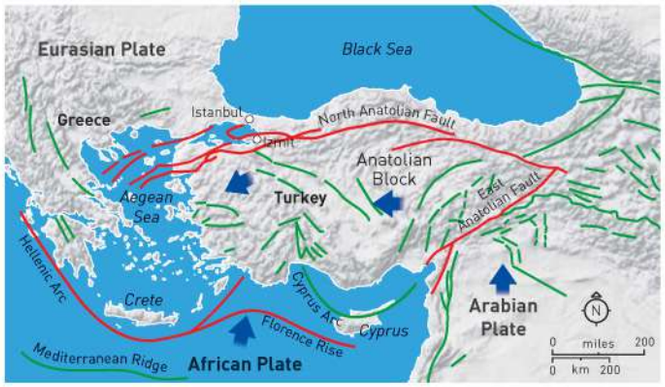
FAULT LINES AROUND THE WORLD

When the first satellite images of the continents became available in the early 1970s, scientists were stunned to see long, knife-like scars in the landscape, in some cases running for hundreds or even thousands of kilometres. A French geologist, Paul Tapponnier, who had been studying these images of Central Asia, was one of the first to realize that what he was looking at were fault lines in Earth's crust, along which there had been large shifts in the landscape. Tapponnier's work revealed one of the largest fault lines on land – the Altyn Tagh Fault in northern Tibet. Many other giant fault lines are now recognized, such as the San Andreas Fault in California, the Denali Fault in Alaska, and the Alpine Fault in New Zealand. All these faults occur where the tectonic plates are moving relative to each other.

An example is where coastal California is sliding northwards along the San Andreas Fault, with a right lateral sense of motion, taking up the motion of the Pacific Plate relative to the North American Plate. Beneath the world's oceans even bigger fault lines lie hidden, forming where the sea floor is spreading apart or slipping beneath a neighbouring continent. Earthquakes provide the key to understanding the significance of these faults, because the seismic waves generated when a fault ruptures tell us the amount and direction of movement.

COMPLEX FAULT LINES IN TURKEY

The countries of the Eastern Mediterranean are geologically very active, with many earthquakes triggered by movement along the large number of fault lines in the region. The African and Arabian tectonic plates are moving northwards, colliding with Eurasia. Turkey is forming a "micro-plate" caught between the bigger plates and pushed out westwards along two major strike-slip faults – the North and South Anatolian Faults – towards the subduction megathrust along the Hellenic Arc. There are many smaller fault lines too, especially in the Aegean region of Greece. Nowhere escapes the danger of a deadly quake.



KEY
- Active fault lines
- Other fault lines
- Plate movement

Faults in the Eastern Mediterranean
The red lines show the major active fault lines. However, there are many other faults, shown in green, which may or may not be active. Movement on all these faults is part of the motion of the African Plate, pushing northwards into Eurasia at a rate of about 10mm (0.4in) per year.



Kaynasli, Turkey
Rescue workers sift through houses and vehicles destroyed by collapsed apartment buildings during a powerful earthquake that measured 7.2 on the Richter scale in Northern Turkey, on 12 November 1999.

MEASURING EARTHQUAKES

Anybody close to an earthquake will feel the ground shaking violently for a few moments. However, these felt vibrations are just part of a pattern of seismic wave vibrations associated with the earthquake, which can be detected by sensitive instruments around the globe called seismometers. The details of this wave pattern provide seismologists with a rich source of data that can be used to investigate both the causes and consequences of an earthquake.

MAGNITUDE SCALES

Seismologists have come up with various ways to describe the amount of energy released during an earthquake. The original Richter scale was based on the magnitude of displacement recorded on a particular type of seismometer at a known distance from the epicentre. Today it is quoted as moment magnitude, which is similar but it is calculated from seismic vibrations on any seismometer. The moment magnitude can be interpreted in terms of the amount of slip that has occurred on the earthquake-triggering fault multiplied by the size (area) of the fault. Both the Richter and moment magnitude scales are logarithmic. An increase of one unit on the scale corresponds to about a 30-fold increase in energy.

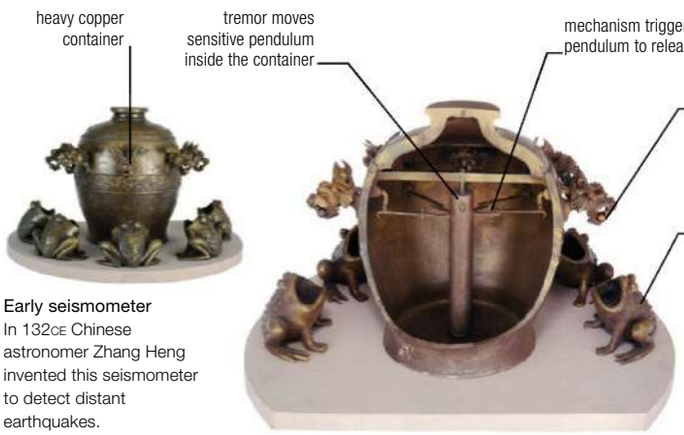
> "THE HIGHEST MAGNITUDES ASSIGNED SO FAR... ARE ABOUT 9, BUT THAT IS A LIMITATION IN THE EARTH, NOT IN THE SCALE."
>
> **CHARLES RICHTER**, US SEISMOLOGIST, 1980



DIGITAL SEISMOGRAPHS
Data from seismometers around the world is fed into computers belonging to earthquake research stations, such as this one in the Philippines.

SEISMOMETERS

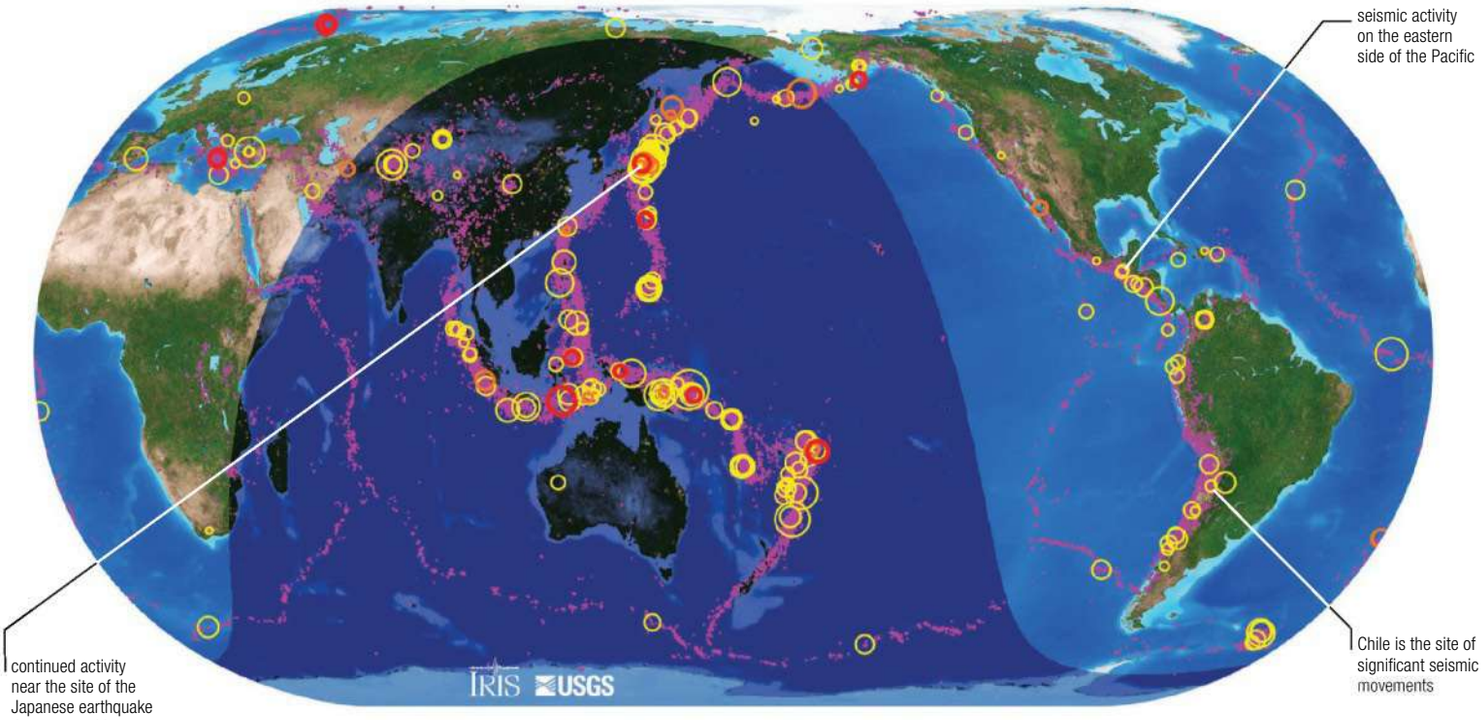
A seismometer is a delicate instrument designed to measure seismic vibrations during an earthquake. It works on the simple principle that the recording part is free to move with the Earth while the bulk of the instrument, which is securely anchored to the ground by a heavy weight, remains stationary. A great step forward in the early 19th century was a neat portable model that could be carried by scientists to areas of seismic activity. Until recently, these vibrations were recorded by a vibrating pen, scratching out a trace called a seismograph on a rotating drum. Modern digital instruments record the vibrations electronically, and the data are processed and stored in a small computer. Readings from several seismometers are passed to a central recording station where the data is analysed. Warnings of serious earthquake activity may then be transmitted to radio or television stations to alert the public. GPS devices are also used to measure the extent of shifts in Earth's surface during earthquakes. Individual, solar-powered devices transmit information from out in the field to research stations.

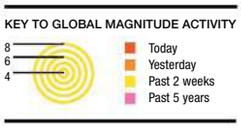


Early seismometer
In 132CE Chinese astronomer Zhang Heng invented this seismometer to detect distant earthquakes.



Recent seismometer
This 1965 model is a Willmore Portable seismometer, capable of picking up and recording much more detailed seismic activity.





GLOBAL SEISMIC MONITORING
This snapshot of seismic activity on 14 April 2011 was recorded by the Global Seismographic Network. The location and magnitude of earthquakes is calculated from this information.

TRACKING GLOBAL SEISMIC ACTIVITY

The Global Seismographic Network, with contributions from a number of countries, is a global state-of-the-art, digital seismic network of seismometers, providing free, real-time data. The instruments are capable of measuring and recording all seismic vibrations, ranging from high-frequency, strong ground motions near an earthquake to the slowest vibrations from a distance away. With the USGS (US Geological Survey), this is the principal source of data for earthquake locations.



GPS INSTRUMENTS
The Global Positioning System (GPS) is used to accurately measure displacements of marker points before, during, and after an earthquake.

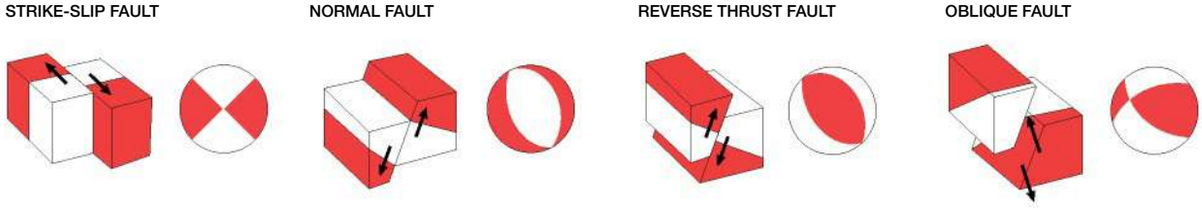
FOCAL MECHANISM

The focal mechanism is a method to indicate the nature of the fault movement that triggered an earthquake. The angle of slip and type of fault movement – such as normal, strike-slip, thrust fault, or reverse thrust (see pp.126–127) – can be inferred from graphical representations termed "beach balls". The coloured areas indicate where the first vibrations of P waves (see pp.126–127) pushed or pulled, and this makes the distinctive beach ball pattern. Seismologists use these icons when they produce maps of fault lines to show the orientation of movements on actual faults.



FOCAL MAP
This segment of a map shows fault lines with focal mechanisms and moment magnitude measurements around the site of the 2010 Haiti earthquake.

BEACH BALLS
The "beach ball" diagrams describe the pattern of seismic waves for distinct types of fault movement. The blocks show the type of fault movement.




SIRVIENDO



MEXICO CITY EARTHQUAKE

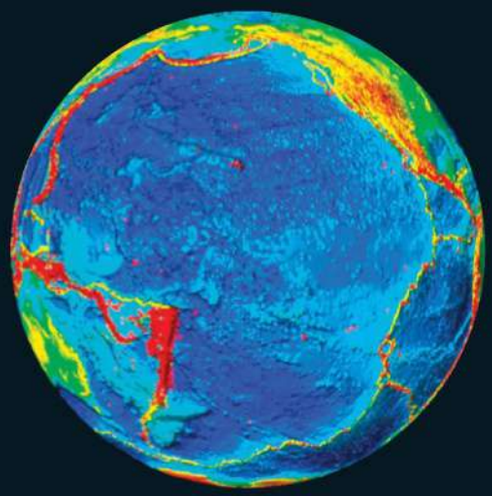
The 1985 Mexico City earthquake measured 8.0 on the Richter scale and caused about 9,500 deaths. The earthquake was located off the Mexican Pacific coast, in a subduction zone more than 350km (220 miles) away. Due to its strength and the fact that Mexico City sits on an old lakebed, the city suffered major damage, with 400 buildings collapsing.

SUBDUCTION EARTHQUAKES

In a subduction zone, especially where the sea floor slides beneath a continent, movement on large thrust faults slice and pile up rocks, building a mountain range such as those found along the Pacific Ring of Fire. These faults are capable of rupturing suddenly, triggering the largest earthquakes on the planet.

SUBDUCTION ZONES AND MEGATHRUSTS

The Pacific Plate is sinking back into Earth's interior in a series of subduction zones that follow the edges of the surrounding continents. Here, the ocean floor rubs against the overlying plate along a giant, gently inclined fault known as a megathrust. Between earthquakes, where the rocks are relatively cold and strong, the two plates are locked together and the motion of the plates is absorbed by squeezing and distortion of the rocks. Eventually, the forces become too great and the fault suddenly ruptures in a great earthquake. The resulting slip raises or drops the seabed or ground surface. The largest earthquakes of this type – like the one in Japan in 2011 – can reach magnitude-9, and displaced water generates devastating tsunamis.



RING OF FIRE

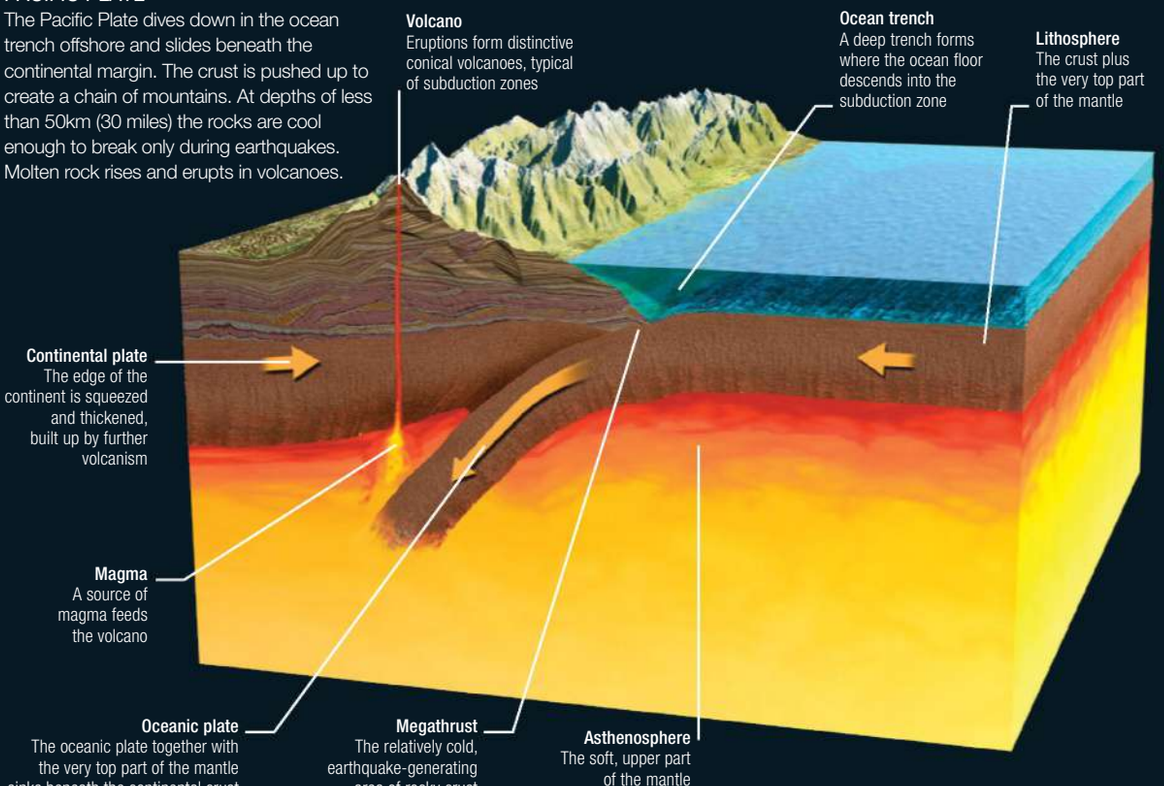
This map shows the depth of the sea floor and elevation of the continents along the margins of the Pacific Ocean. A deep ocean trench and a line of active volcanoes follow the Pacific Rim, defining a series of subduction zones in the so called Ring of Fire.

KEY

- Earthquakes since 1980 at magnitude 5 and above
- Plate boundaries

PACIFIC PLATE

The Pacific Plate dives down in the ocean trench offshore and slides beneath the continental margin. The crust is pushed up to create a chain of mountains. At depths of less than 50km (30 miles) the rocks are cool enough to break only during earthquakes. Molten rock rises and erupts in volcanoes.



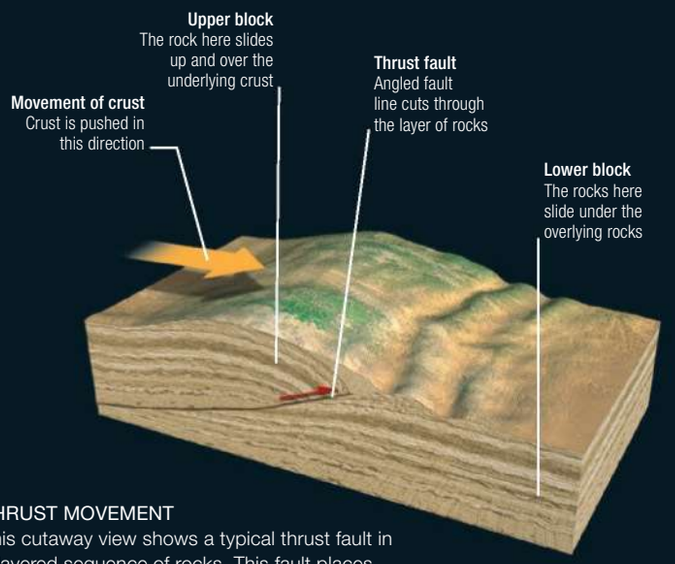




THE GREAT ALASKAN EARTHQUAKE
On 27 March 1964, sudden slip on a megathrust under southern Alaska triggered the largest recorded earthquake in North America, severely damaging the city of Anchorage. A devastating tsunami followed the magnitude-9.2 quake.

THRUST FAULTS

Thrust faults are defined as faults that are inclined at angles less than 45°, where the overlying rocks slide up and over the underlying rocks. Faults like this tend to occur in layered rocks, sometimes inclined at only a few degrees where they follow the rock layers. A megathrust is merely a very large thrust, and can extend for thousands of kilometres along its length. The biggest megathrusts are found in subduction zones. Large thrusts also form the edges of the world's largest mountain ranges.

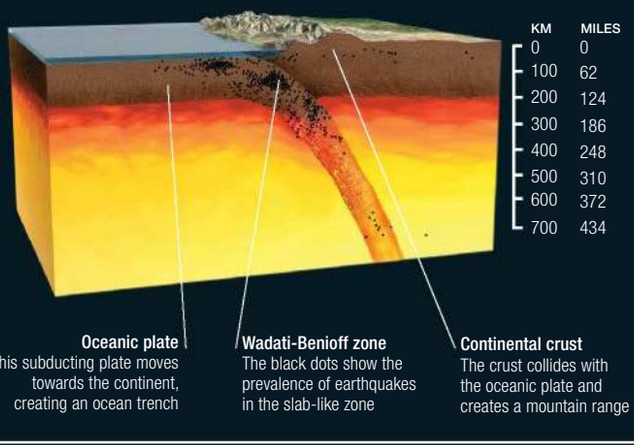


THRUST MOVEMENT
This cutaway view shows a typical thrust fault in a layered sequence of rocks. This fault places deeper, older rocks above younger rocks.

WADATI-BENIOFF ZONE

In a subduction zone, where the oceanic plate dives into Earth's interior, there is intense earthquake activity. However, the earthquakes do not occur only along the megathrust, where the oceanic plate rubs against the overlying plate. There are also earthquakes in the oceanic plate itself, down to depths of nearly 700km (435 miles). This phenomenon was first described in the early 20th century by seismologists Kiyoo Wadati from Japan and Hugo Benioff from the USA. They related the activity of many small earthquakes in the Pacific to a subducting oceanic plate, as it was stretched and squeezed deep in the Earth.

Deep earthquakes
This illustration shows the depth of earthquakes that originate in the slab-like Wadati-Benioff zone. In the Pacific Rim, this slab plunges to a depth of 700km (435 miles).



CONCEPCIÓN 2010

In 1835, while voyaging on the ***Beagle*** ,the English naturalist Charles Darwin witnessed a massive earthquake near Concepción, Chile. Many years later, in 1960, the residents of this same city experienced a magnitude–9.5 earthquake – the largest ever recorded with modern instruments. On Saturday, 27 February 2010, history repeated itself, as a magnitude–8.8 earthquake struck the coastal region of central Chile, again near the town of Concepción. The earthquake was felt across a large area of South America, including Brazil, Bolivia, and Argentina. It triggered a Pacific-wide tsunami, and killed at least 521 people, injured 12,000, and left hundreds of thousands displaced. The tsunami damaged or destroyed many buildings and roads along the coast in the vicinity of Concepción, and damaged boats and a dock as far away as San Diego, California, USA. More than 2m (6.5ft) of uplift along the coast was observed near Arauco. The earthquake was the result of 5 to 15m (16 to 49ft) of slip on the megathrust along the plate boundary between the South American Plate and the subducting Nazca Plate, rupturing a zone around 500km (310 miles) long.



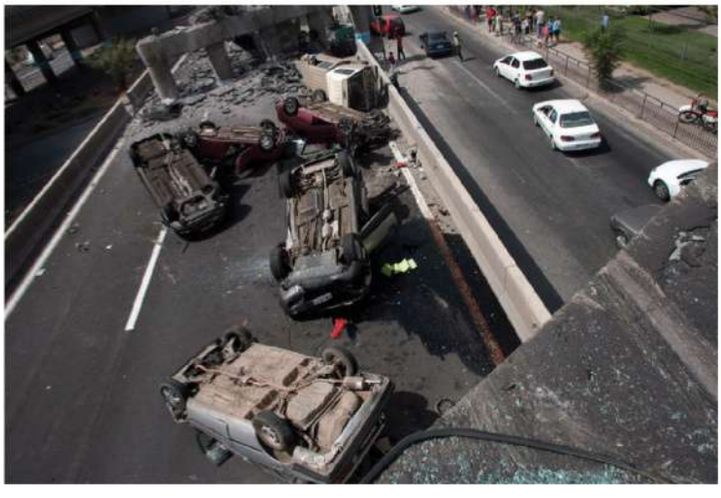
27 FEBRUARY 2010	
Location	Concepción, Chile
Type	Megathrust
Fatalities	521

8.8 MAGNITUDE OF THE EARTHQUAKE



MASS DAMAGE
The considerable force that was unleashed by the earthquake caused these large apartment buildings in Santiago, Chile, to buckle and lean at precarious angles.

DISASTER STRIKES



1 THE GROUND SHAKES
The violent shaking during the earthquake was enough to overturn these cars travelling along a road in Santiago, Chile. A maximum ground acceleration of 0.65g was recorded at Concepción.

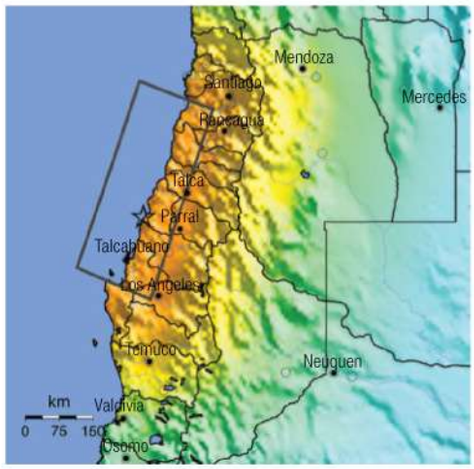


2 THE TSUNAMI STRIKES
Within 30 minutes of the main shock, a tsunami washed onshore, created by the sudden movement of the sea floor up to 100km (60 miles) from the coast. This picture shows the destruction caused by the tsunami in the Chilean coastal town of Talcahuaro.





3 LOOKING FOR SURVIVORS
Rescue workers climb into a collapsed building in Santiago, looking for survivors trapped inside. An estimated 500,000 homes in Chile were severely damaged by the earthquake and ensuing tsunami.



SHAKE MAP
The greatest shaking is clearly defined in a region about 500 km (310 miles) long, following the coast of Chile. The region is underlain by the gently inclined megathrust where the ocean floor (Nazca Plate) is sliding beneath part of South America. During the earthquake, a sudden slip on the megathrust released a vast amount of seismic energy that violently shook the region.

Percieved shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Potential damage	None	None	None	Very light	Light	Moderate	Moderate heavy	Heavy	Very heavy
Intensity	1	2–3	4	5	6	7	8	9	10+

EARTHQUAKE RESCUE TECHNOLOGY

In high-risk areas, buildings are constructed to control vibration and remain stable in the event of an earthquake. However, the destructive power of an earthquake can leave buildings in ruins, so rescue technology is crucial in the search for people trapped under rubble. Highly trained sniffer dogs take minutes to locate people buried deep in the debris. Rescuers then operate heat imaging and listening devices to confirm the presence of, and communicate with, any survivors. More recently, robots have been developed that are equipped with wheels to negotiate obstacles, cameras to relay images back to the controllers, and infrared sensors to detect people in the rubble.



SURVIVOR-DETECTING ROBOT
This device is a flexible robot developed in Japan to aid the search for survivors among the debris of earthquake and tsunami ravaged regions. It rotates with a snake-like motion, enabling it to slide over the ground and glide through water. Sensors detect the presence of survivors.

"THREE MINUTES IS AN ETERNITY. WE KEPT WORRYING THAT IT WAS GETTING STRONGER, LIKE A TERRIFYING HOLLYWOOD MOVIE."

DOLORES CUEVAS, SANTIAGO HOUSEWIFE

SICHUAN, CHINA 2008

The magnitude–7.9 earthquake that struck eastern Sichuan, 90km (55 miles) from the city of Chengdu in May 2008 was one of the most destructive earthquakes to strike China in more than 30 years, with strong aftershocks continuing for several months. At least 69,000 people were killed, hundreds of thousands were injured or missing, and many tens of millions displaced or made homeless by the disaster. More than five million buildings collapsed, with landslides and rockfalls blocking roads and railway lines. The deadly earthquake was felt throughout much of China and as far afield as Bangladesh, Taiwan, Thailand, and Vietnam, where buildings swayed with the tremor. The earthquake occurred when a reverse fault slipped between 2 and 9m (7 and 30ft), extending for about 200km (125 miles) along the southeastern edge of the Longmen Shan Mountains. This region lies at the eastern edge of the vast collision zone between India and Central Asia. Here, the convergence of the two plates has also resulted in the uplift of the Himalayas and Tibetan Plateau. The Longmen Shan region has previously experienced destructive earthquakes. In August 1933, a magnitude–7.5 earthquake killed more than 9,300 people.



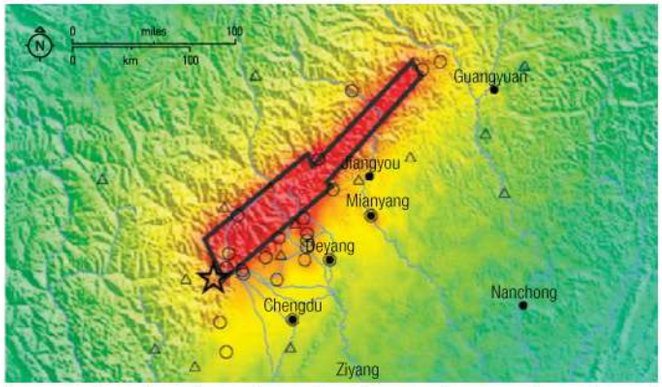
12 MAY 2008	
Location	Eastern Sichuan, China
Type	Thrust fault
Fatalities	Approximately 69,000

7.9 ON THE MOMENT MAGNITUDE SCALE

DESTRUCTIVE FORCE
The earthquake annihilated cities and villages in Sichuan Province. In the city of Beichuan alone, it is estimated that 80 per cent of the buildings were reduced to rubble.

EASTERN SICHUAN SHAKE MAP

This colour-coded map shows the intensity of shaking, from red (most intense) to green (moderate). The most intense shaking occurred in a long zone, extending from the earthquake epicentre at the far southwestern end and following the line of where the Longmen Shan Fault ruptured at depth, which was more than several hundred kilometres in length.



Perceived shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Potential damage	None	None	None	Very light	Light	Moderate	Moderate heavy	Heavy	Very heavy
Intensity	1	2–3	4	5	6	7	8	9	10+

DISASTER AND RESCUE



1 RUSHING WATER
"Quake lakes" (see p152-153) formed when landslides triggered by the earthquake blocked rivers. Here, rushing water from a breached quake lake flows through devastated Beichan.



2 RESCUE EFFORTS
Search and rescue teams helped locate and dig out survivors trapped in the debris of collapsed buildings in Beichan.



3 TEMPORARY SHELTERS
Prefabricated houses for quake victims were hastily erected in hard-hit Wenchuan, one of the cities closest to the epicentre.

> "THIS IS THE MOST DESTRUCTIVE EARTHQUAKE SINCE THE PEOPLE'S REPUBLIC OF CHINA WAS FOUNDED [IN 1949] AND HAS AFFECTED THE WIDEST AREAS."
>
> **WEN JIABAO**, CHINESE PREMIER



BIRTH OF A FAULT LINE
This aerial view of fields shows a new fault line created during the 2011 earthquake near Christchurch, New Zealand. An area of ground has been torn for a distance of nearly 30km (18.5 miles) across farmland. Where the fault line crosses a water-filled ditch, the right-lateral displacement is clear, and the ditch is offset horizontally by a few metres.

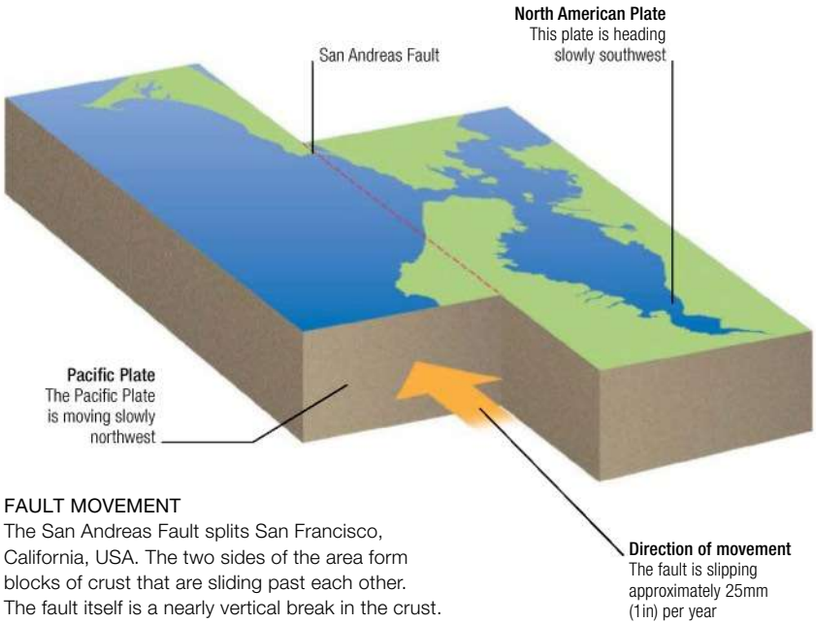


STRIKE-SLIP EARTHQUAKES

When two plates slide past each other, strike-slip fault lines form in the crust, which can suddenly rupture during earthquakes. From space, these fault lines can clearly be seen across the continents as giant scars in the landscape.

SLIPPING AND SLIDING

A strike-slip fault forms a deep break in the crust, extending to depths of tens of kilometres. As one side moves relative to the other, either to the left (left-lateral dIsplacement) or the right (right-lateral displacement), the rocks become intensely fractured, sometimes ground down into a fine, clay-like powder. The actual movement during an earthquake usually occurs as a series of jerks because the blocks stick and then slip past each other. For example, the San Andreas strike-slip fault in California, USA, broke during the 1906 earthquake, moving about 5m (17ft) with a right-lateral displacement. Measured over geological periods of time, this fault slips at a rate of about 25m (80ft) every thousand years while it absorbs motion between the Pacific and North American plates. An earthquake on this part of the fault occurs on average every 200 years.



FAULT MOVEMENT
The San Andreas Fault splits San Francisco, California, USA. The two sides of the area form blocks of crust that are sliding past each other. The fault itself is a nearly vertical break in the crust.



OFFSETTING LANDSCAPE

Over millions of years, the displacements during individual strike-slip earthquakes build up. On major strike-slip faults, these displacements can reach hundreds of kilometres, slicing up and offsetting the bedrock by staggering amounts. Geologists used to believe that such large offsets on strike-slip faults were impossible, because nobody could understand what happened at the ends of the fault lines. Now, with the theory of plate tectonics, it is clear that the faults ultimately connect with other plate boundaries, where the ocean floor is sinking back into the Earth, or is being created at mid-ocean ridges. Thus, over the past 20 million years, the roughly 500-km (310-mile) strike-slip offset of the rocks along the San Andreas Fault, or a similar amount for New Zealand's Alpine Fault, is part of the destruction and creation of oceans.

1906 EARTHQUAKE, SAN FRANCISCO, CALIFORNIA
These multi-story wooden houses on Howard Street in San Francisco tilted over, but remained more or less intact during the powerful 1906 earthquake that shook the city.





KOBE EARTHQUAKE
In January 1995 a strike-slip earthquake of magnitude-6.8 struck the city of Kobe, Japan, killing thousands and causing major damage. Japan is in a complex tectonic setting between Philippine, Pacific, Eurasian, and Okhotsk plates.

IZMIT 1999

On 17 August 1999, at 3:00am, a magnitude–7.4 earthquake struck northwestern Turkey, about 11km (7 miles) from the town of Izmit. This devastating earthquake was felt more than 500km (310 miles) away on the south coast of Crimea, in the Ukraine. It was caused by a sudden movement on the major fault line in the region – the North Anatolian Fault – with up to 5m (16ft) of right lateral strike-slip displacement on a segment of the fault extending for about 120km (75 miles) within 50km (30 miles) of Turkey's largest city, Istanbul, where 13 million people live. The main shaking lasted for 37 seconds, with maximum ground accelerations of up to 0.4g. With at least 17,118 people killed and the estimated cost of damage put at $6.5 billion, the earthquake was both a major humanitarian tragedy and an economic disaster. The Izmit earthquake is just the latest in a sequence of earthquakes over the past 60 years that have been moving closer to Istanbul. Each earthquake was caused by the sudden breaking of segments of the North Anatolian Fault. The 1999 disaster filled in an earthquake gap on this fault that had been identified by geophysicists as likely to rupture.

A CITY IN RUINS



1 DESTRUCTION AND MASS DAMAGE
Many cities in the region, including Izmit, Adapazari, and Istanbul, suffered major damage from shaking, with the destruction of apartment buildings, mosques, and historic monuments.



17 AUGUST 1999

Location	Izmit, Turkey
Type	Strike-slip
Magnitude	7.4

85,000

THE NUMBER OF BUILDINGS DESTROYED



A HUMAN TRAGEDY
Relatives search for belongings and survivors among the debris of concrete apartment blocks, which crumbled all around them during the earthquake.

> "WHEN IT HIT, I FELT HELPLESS – LIKE BEING THROWN EVERY WHICH WAY IN A FRYING PAN."
>
> **ERCÜMENT DOĞUKANOĞLU**, NAVAL CAPTAIN



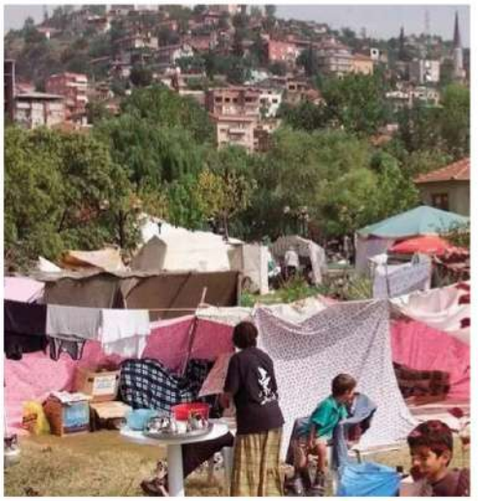
THE NORTH ANATOLIAN FAULT
The North Anatolian Fault is a major strike-slip fault line that runs nearly 1,500km (930 miles) through northern and western Turkey. It marks the southern edge of the Eurasian Plate, slipping today at about 25mm (1in) per year, with a right-lateral displacement.



2 OIL REFINERY FIRES
A tower at the Tupras oil refinery collapsed, starting a major fire that took several days to bring under control. More than 700,000 tonnes of oil were stored at the refinery.



3 INJURIES AND SURVIVAL
Nearly 50,000 people were injured during the earthquake, trapped in their houses and apartments when the earthquake struck during the early hours of the morning.

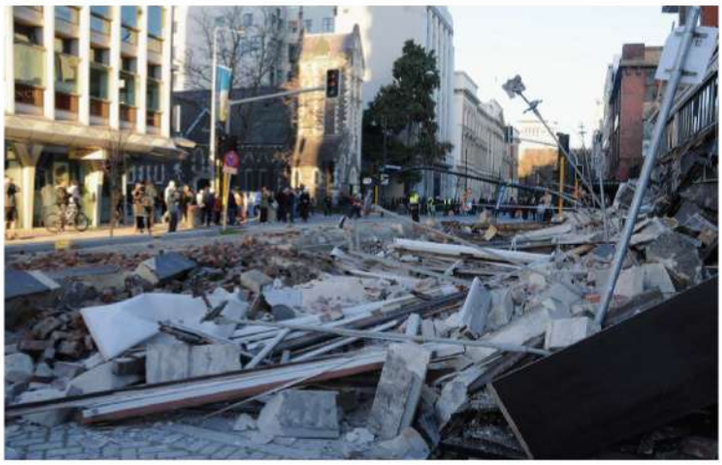


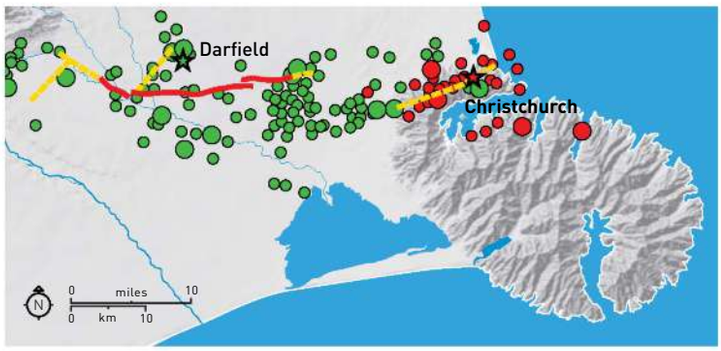
4 HOMELESSNESS AND REBUILDING
Few buildings in Izmit were constructed to withstand earthquakes. Whole districts collapsed and about 500,000 people lost their homes during the 37-second tremor.



CHRISTCHURCH 2011

On 22 February 2011, at about midday, an earthquake measuring 6.3 on the Richter scale struck the major city of Christchurch on South Island, New Zealand, with its epicentre close to the port of Lyttleton. Ground accelerations of nearly 2g rocked the central business district, destroying more than a third of the buildings. Extensive liquefaction (see p.152) in the eastern suburbs of Christchurch badly damaged residential properties. There were landslides in the Port Hills, to the south of Christchurch, and dislodged boulders rolled through the suburbs, leaving a trail of destruction. More than 100 people were killed, while 1,500 were injured. This earthquake was part of the protracted sequence of aftershocks following an earthquake on 4 September 2010, about 20km (12 miles) to the west of Christchurch in Darfield. There was no loss of life after this magnitude–7.1 earthquake, although it damaged





KEY

- Sub-surface fault rupture
- Greendale Fault
- M-4 – 4.9 earthquake
- M-5 – 5.9 earthquake
- Earthquakes since 22 Feb 2011
- Earthquakes before 22 Feb 2011
- **Aftershock** M-6 – 6.9 22 Feb 2011
- **Main shock** M-7 – 7.9 4 Sept 2010



22 FEBRUARY 2011	
Location	Christchurch, New Zealand
Type	Thrust fault
Fatalities	Approximately 166

100,000

BUILDINGS DAMAGED (APPROXIMATELY)

A DEADLY AFTERSHOCK

Although the Christchurch earthquake was a relatively moderate earthquake, having nearly 30 times less energy than the magnitude–7.1 Darfield earthquake in September 2011, it was far more destructive. Seismologists believe a number of factors led to this. Firstly, fault movement during the 22 February earthquake was closer to Christchurch, and was only about 5km (0.62 miles) below the surface of its southern suburbs. In addition, the way the fault ruptured focused much of the energy of the earthquake in the central business district of Christchurch, which sits on relatively poorly consolidated sediments prone to many of the deaths occurred in two downtown buildings that failed to withstand the shaking and collapsed almost completely, crushing the people inside.

> "THE PHONE LINES AND WATER ARE NOT WORKING. THE ROADS ARE GRIDLOCKED AS THE CITY IS BEING EVACUATED."
>
> **CHRISTOPHER STENT**, EYEWITNESS



SEARCHING FOR SURVIVORS
The 22 February earthquake struck during office hours and trapped scores of people underneath mounds of rubble. Rescue workers had an enormous task searching for survivors amid the debris.

15,000

The approximate number of earthquakes that occur in New Zealand every year. Most of these are minor and only 10 or fewer of these would have a magnitude in excess of 5.0. The country is located on the border of the Australian and Pacific plates, which are colliding, making it prone to earthquakes.

THE CHRISTCHURCH CATHOLIC CATHEDRAL
The February 2011 earthquake caused irrevocable damage to several iconic cathedrals in Christchurch, including the Christchurch Catholic cathedral. Two bell towers in the front of the cathedral collapsed, bringing down most of its front façade.





SEARCHING THE RUBBLE
Rescue workers search for survivors near the Canterbury Television (CTV) building in the heart of Christchurch, New Zealand. The CTV building completely collapsed during the February 2011 earthquake and was the focus for intense efforts to find survivors. Ninety-four bodies were recovered from the ruins.

SEISMIC DESTRUCTION

Earthquakes wreak destruction on a vast scale. Not only are man-made structures damaged but the very ground itself is altered, liquifying soil and creating quake lakes. This does not just occur during the main shock. Numerous aftershocks can be sufficiently violent to cause damage during the vulnerable recovery period. In some cases, foreshocks can be a warning of what is to come.

FORESHOCKS AND AFTERSHOCKS

Earthquakes are not isolated events. This is because rocks do not just break along one fracture, but on numerous fractures or faults – and each break will trigger its own small earthquake. The main shock is triggered by the largest break, but there may be precursor breaks – triggering so-called foreshocks that have the potential to be large events in themselves – and many subsequent breaks, triggering a long sequence of aftershocks that can continue for years. It was hoped that the detection of foreshocks could be used to predict an imminent main shock, but in practice foreshocks are only recognized after the main shock has occurred. The 2002 earthquake in Sumatra is now recognized as a foreshock, occurring two years before the massive magnitude 9+ 2004 Indian Ocean earthquake. Back in 2002, this was not known. The 4 September 2010 magnitude-7.3 Darfield earthquake, which was focused just outside Christchurch in New Zealand, had numerous magnitude-5+ aftershocks in the following months, culminating in a magnitude-6.3 earthquake on 22 February 2011, which destroyed much of the central business district of Christchurch and killed 166 people. The whole earthquake sequence is now recognized as the result of a propagating fault line, moving towards the east. Although an earthquake can relieve the accumulation of stress in one part of a fault line, it can mean that there is more likelihood of another quake in a different part of the fault.



SUMATRA AFTERSHOCK
A view of the destruction left by the massive earthquake that hit the island of Nias off the coast of Sumatra in March 2005. This was an aftershock following the huge earthquake in the region in December 2004.

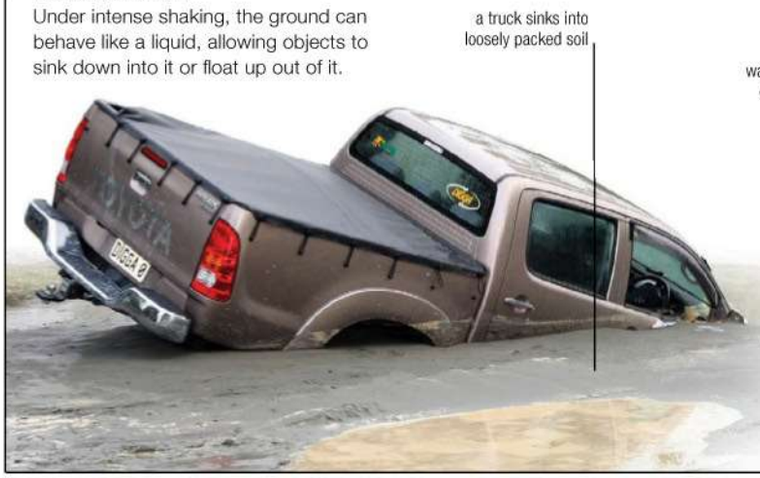
12 COSTLIEST EARTHQUAKES IN LAST 100 YEARS

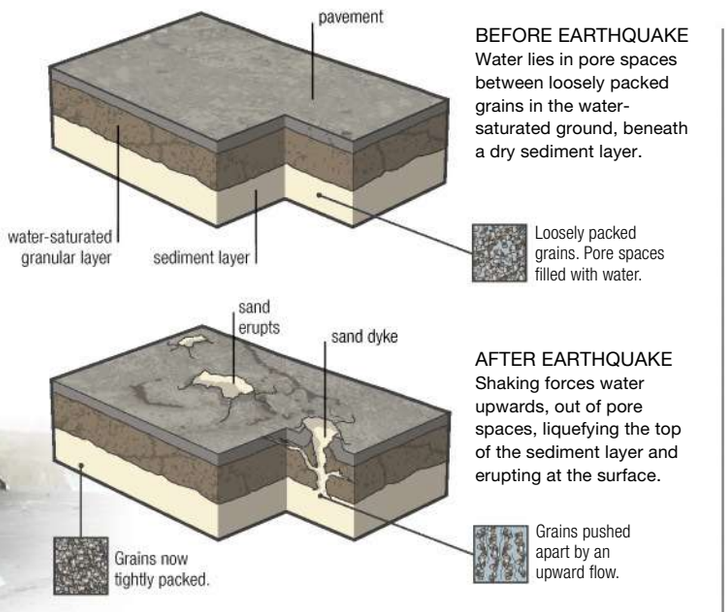
NO	YEAR	COUNTRY	COST OF DAMAGE/ REBUILD (IN US$)
1.	2011	Tohoku, Japan	more than 300 billion
2.	1995	Kobe, Japan	131.5 billion
3.	1994	Northridge, California, USA	20–40 billion
4.	2004	Niigata, Japan	28 billion
5.	1988	Armenia	14.2–20.5 billion
6.	1980	Irpinia, Italy	10–20 billion
7.	1999	Taiwan	9.2–14 billion
8.	1999	Izmit, Turkey	6.5–12 billion
9.	1994	Kuril Islands, Russia	11.7 billion
	1994	Hokkaido, Japan	11.7 billion
11.	2010	Christchurch, New Zealand	11 billion
12.	2004	Indian Ocean	7.5 billion

LIQUEFACTION PROCESS

In water-saturated ground, shaking during an earthquake can force the water out of pore spaces, turning the ground into a liquid. The water then erupts at the surface – known as sand boiling – bringing up with it mud and sandy material, and causing local flooding. Heavy buildings or cars may subside into the liquefied ground.

LIQUID GROUND
Under intense shaking, the ground can behave like a liquid, allowing objects to sink down into it or float up out of it.





BEFORE EARTHQUAKE
Water lies in pore spaces between loosely packed grains in the water-saturated ground, beneath a dry sediment layer.

Loosely packed grains. Pore spaces filled with water.

AFTER EARTHQUAKE
Shaking forces water upwards, out of pore spaces, liquefying the top of the sediment layer and erupting at the surface.

Grains pushed apart by an upward flow.

OIL REFINERY FIRE
Damage from the earthquake and tsunami in Japan in March 2011 caused fires to break out at an oil refinery in Chiba, near Tokyo.

FIRES

Fires are a serious potential hazard in an earthquake-hit area. For example, when an earthquake severely shakes the ground beneath a city, electricity cables, gas pipes, and oil installations can be damaged or broken. Electrical arcing (a continuous discharge of electricity) or overheating often lead to explosions and fires that can rage through a city. Much of the loss of life during the San Francisco 1906 earthquake was due to uncontrollable fires that started this way. A new hazard has become apparent in the recent earthquake in Japan in 2011, where damage to electrical supplies during the quake and tsunami led to overheating and fires in the nuclear power plant at Fukushima. Partial core meltdown and hydrogen explosions led to leaks of radiation.

FLOODING

Landslides triggered by an earthquake may block rivers, causing widespread flooding. Debris shaken loose by the earthquake falls into rivers and blocks the flow. Water begins to pool behind the blockage, which is unstable, and can burst to flood to the surrounding area. The 2008 Sichuan earthquake in China (see pp.140–141) triggered landslides that dammed several rivers. Massive amounts of water gathered behind the dams forming a number of quake lakes. The lakes threatened to flood cities already hit by the earthquake and they had to be carefully drained to prevent this. Man-made dams that have been damaged by an earthquake can also trigger flooding. If there is heavy rain after an earthquake, blocked drains may result in urban flooding.

DAMAGED CITY
This image shows the earthquake-hit city of Beichuan in China's southwestern province of Sichuan on 27 May 2008. Many buildings had been destroyed by the earthquake on 12 May 2008 and landslides in the mountainous region were triggered.



QUAKE LAKES
This image taken on 10 June 2008 shows how the area became flooded when rivers in the region were blocked by debris from landslides. A large body of water quickly grew behind these dams and started to flood the damaged city with a huge quake lake.



BAM 2003

On 26 December 2003, at about 5:30 in the morning, a magnitude–6.6 earthquake struck the ancient town of Bam, located on the old Silk Road in southeastern Iran. The ground shook with such acceleration that the historic citadel, the Arg-e Bam – which was one of the largest mud-brick constructions in the world, and at least 2,000 years old – was completely destroyed. The huge number of casualties, which included about 30,000 fatalities, with a similar amount injured, and about 100,000 people made homeless – was due to the roofs of many houses collapsing at a time when most people were still in bed. Buildings as well as roads and infrastructure were damaged. Maximum intensities of shaking were felt in Bam and the nearby town of Baravat. The area around Bam is prone to earthquakes and the epicentre of this earthquake was close to a recognized fault line – the Bam fault, plus there were small local ruptures of the ground surface. However, detailed studies later showed that the main fault movements occurred at depth on a nearby unrecognized fault, involving right-lateral and reverse displacements of the rocks. The Bam earthquake was the result of the forces that have built up because of the northward movement, at a rate of about 3cm (1.2in) per year, of the Arabian Plate, which is colliding with the Eurasian Plate. This has resulted in the rise of the Zagros Mountains, as well as movement of blocks of crust along strike-slip faults in southeastern Iran.



26 DECEMBER 2003

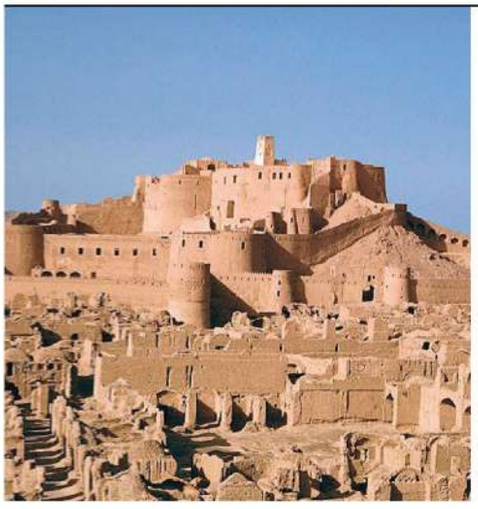
Location	Bam, southeastern Iran
Type	Reverse strike-slip fault
Magnitude	6.6

30,000

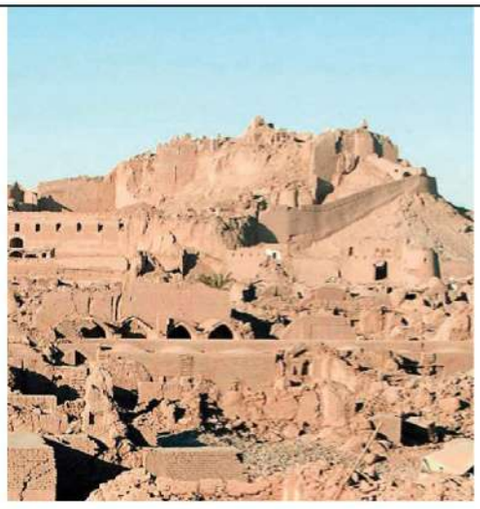
THE APPROXIMATE NUMBER OF PEOPLE KILLED



BUILDINGS DESTROYED
Poor quality construction and materials meant that most properties could not withstand the strong shaking generated by the quake and many houses collapsed.



ANCIENT CITY BEFORE
The citadel of Bam, an ancient fortified area in the north of the modern city of Bam, was constructed 2,000 years ago from mud. It had been well preserved until 2003, when the earthquake struck.



ANCIENT CITY AFTER
This photograph shows the devastation of the Bam citadel following the magnitude–6.6 earthquake in December 2003. Shaking destroyed the mud walls and arches, burying much of the area under debris.



BAM FLATTENED
This is an aerial view of the city of Bam after the 2003 earthquake. The ringed area shows the destroyed Arg-e Bam, or ancient citadel. Much of modern Bam was badly damaged as well.

> "I LOST MY WIFE IN THIS EARTHQUAKE... I AM VERY SAD BUT I THINK BAM'S PEOPLE NEED INTERNATIONAL HELP."
>
> **ASGHAR GHASEMI**, TEHRAN

EARTHQUAKE ZONE

The city of Bam lies in an earthquake-prone area – there are major strike-slip faults in southeastern Iran, including the Bam Fault – which has lead to a long history of earthquakes, including four larger than magnitude 5.6 in the region to the northwest of Bam. However, prior to 2003 the city of Bam itself had no record of significant earthquake damage. Therefore, the massive destruction of the city and its surroundings caught the population unawares. The scale of the disaster prompted a change in international relations with Iran, and at least 44 countries, led by the United States, sent specialist teams to help with rescue and relief. The UN and International Red Cross launched an appeal for aid, raising tens of millions of dollars. The USA sent five airlifts of supplies, including 1,146 tents, 4,448 kitchen sets, more than 10,000 blankets, and 68 tonnes of medical supplies.



TEMPORARY SHELTER
Four months after the earthquake, Iranian children were photographed standing in front of their temporary tent shelter. It was estimated that about three-quarters of all buildings in the area were destroyed, leaving 100,000 people homeless.

QUAKE-TRIGGERED LANDSLIDES

The violent tremors during even a moderate earthquake are enough to shake the ground loose and trigger huge landslides, especially where the ground is steep. In fact, geologists have long considered the scars of ancient landslides in earthquake-prone regions as tell-tale signs of past earthquakes.

UNSTABLE GROUND

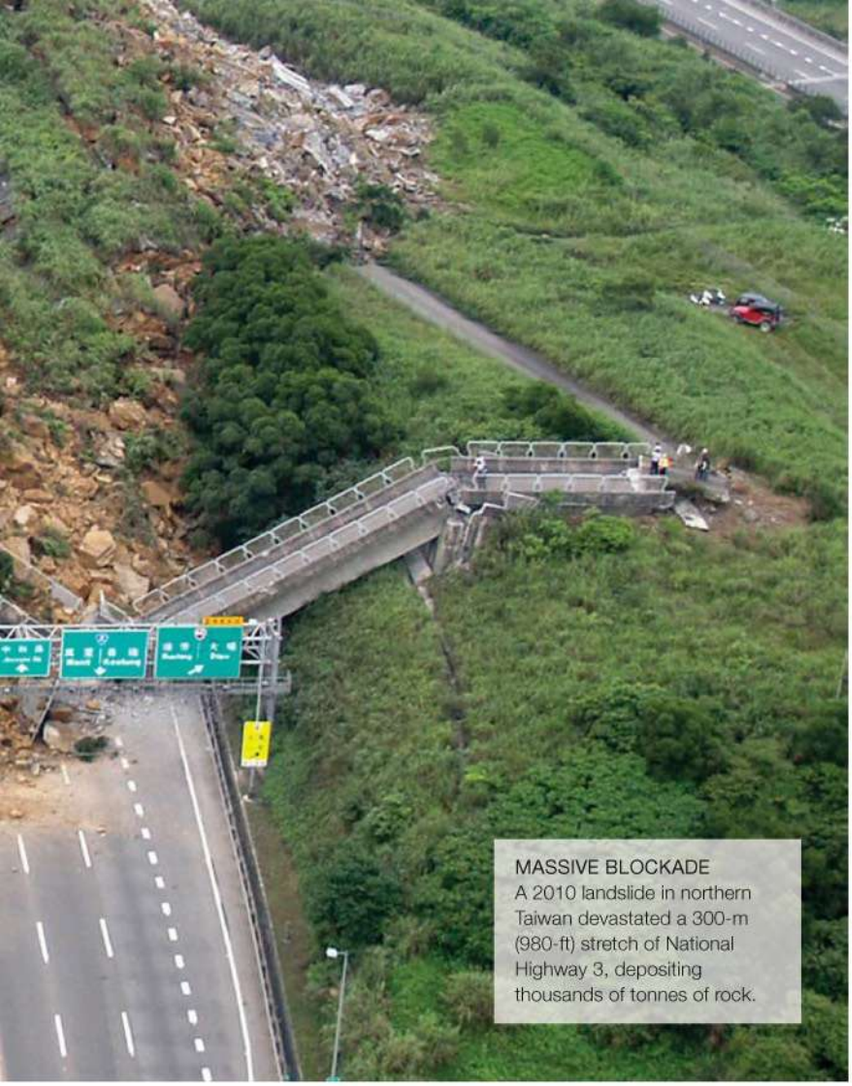
Earth's surface is not flat, but has been moulded by tectonic forces and sculpted by rivers and glaciers into valleys, hills, and mountains that are sloped. Their surface soil and rocks are held in a delicate balance of forces – they cling to the bedrock because of friction and cohesion, while gravity causes them to fall down. Because movements at faults are linked to earthquakes, the most mountainous regions – with the steepest surface slopes – are subjected to the most frequent and intense earthquakes. Accelerations of the ground during an earthquake are easily enough to undo the delicate balance of forces in the surface soil and rocks. In the aftermath of a big earthquake, a landscape may become marked with the scars of landslides, particularly on the steepest slopes. These mark the regions where the shaking of the ground was most intense. The most obvious results are rockfalls, where boulders, already weakened by erosion and sitting loosely on the bedrock, tumble downhill. In addition, shaking of water-saturated soil can squeeze the water out, resulting in a very weak, liquid-like substratum – a process called liquefaction. Vast slumps of soil and rock slip and slide on this weakened layer. Finally, heavy rain after an earthquake may wash much of the loose ground downhill, sometimes in giant mudflows.

ROCK HAZARDS

The tops and bottoms of cliffs or steep ground are very unsafe places during an earthquake. Huge chunks of rock can detach themselves, gathering speed as they fall and crash into buildings and people below. A tumbling boulder during the 2011 earthquake in Christchurch, New Zealand, cut a path of destruction through gardens and houses in a suburb at the foot of some volcanic hills. In rugged and earthquake-prone terrain, geologists use rockfalls as indicators of past earthquakes in the region.



FALLING DANGER
Residents of Wajima, Japan, can be seen carrying their belongings past a huge boulder that fell from a cliff during an earthquake in 2007.



MASSIVE BLOCKADE
A 2010 landslide in northern Taiwan devastated a 300-m (980-ft) stretch of National Highway 3, depositing thousands of tonnes of rock.



BURIED IN MUD
This satellite image shows a town in the Gansu province of China that was submerged after a rain-triggered mudslide flooded the town, burying many alive.



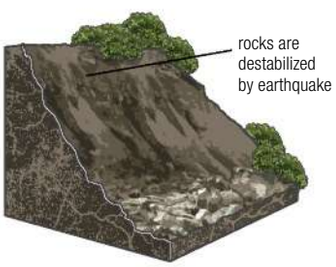
BEICHUAN, CHINA
Evacuees carry their belongings near a landslide site in the Beichuan county of Sichuan Province, China, following an earthquake in May 2008.

THE GANSU MUDSLIDE

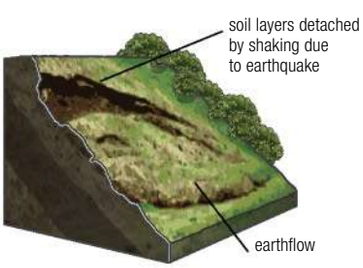
In August 2010, a mudslide occurred in Zhouqu county, in the Gansu Province of China. It was caused by heavy rains falling on steep, weathered ground during the catastrophic 2010 floods in China. Although it was not an earthquake-triggered mudslide, it was typical of mudslides that can happen if heavy rains occur soon after an intense earthquake, washing over ground that has been shaken and weakened. During the 2010 floods, torrential rains in the mountainous region had created sludge-like conditions. Large amounts of mud and rock slid off the steep slopes resulting in a mudslide that buried one village completely and killed about 1,500 people.

LANDSLIDES

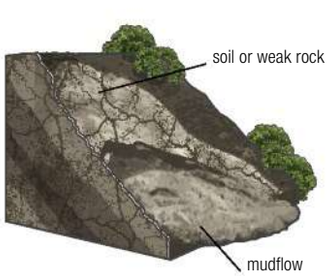
A natural geological process, landslides play an important role in sculpting the landscape. They are a form of what geologists call “slope failure”. An earthquake acts as a trigger, starting a landslide in already unstable ground. Thus, all basic types of slope failure, observed by geologists and illustrated in these diagrams, can occur during an earthquake.



ROCKFALL
Loose or weakened rocks on steep ground or cliff faces will ultimately fall down, accumulating as a pile of scree.



EARTHFLOW
When the soil rests on a smooth rock surface, or is saturated by water, earthquakes easily trigger earthflows.



MUDFLOW
Heavy rain running off steep hillsides, especially after an earthquake, can create mudflows that move downhill.

LIVING WITH EARTHQUAKES

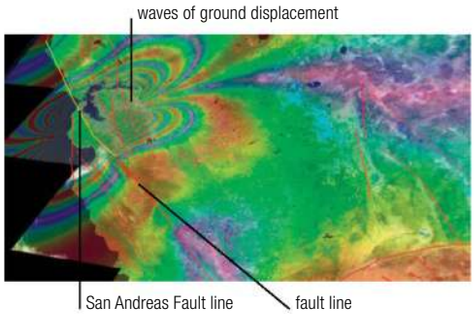
Most of the world's population live in cities located in earthquake-prone areas. Engineers have used their ingenuity to design new buildings and reinforce existing buildings to withstand the huge ground movements during an earthquake. There are also warning systems in place to pick up unusual seismic activity in these zones.

EARTHQUAKE RISK

One of the main long-term goals of scientists is to forecast the next "big one". Current understanding of the earthquake phenomenon suggests that this is many years away, if it is possible, because earthquakes are an uncertain process. Seismologists have tried unsuccessfully to study animal behaviour, natural gas leaks, or sequences of small precursor earthquakes, which might indicate incipient ground motion before the main shock. More promising have been detailed studies of the past history of earthquakes and fault movement in a particular region, combined with measurements of the steady growth of rock strain. These provide insight into the likelihood of a large earthquake in the next few decades or centuries. To date, most attention has been focused on the major fault lines. However, many earthquakes occur on previously unrecognized faults, making prediction more difficult.

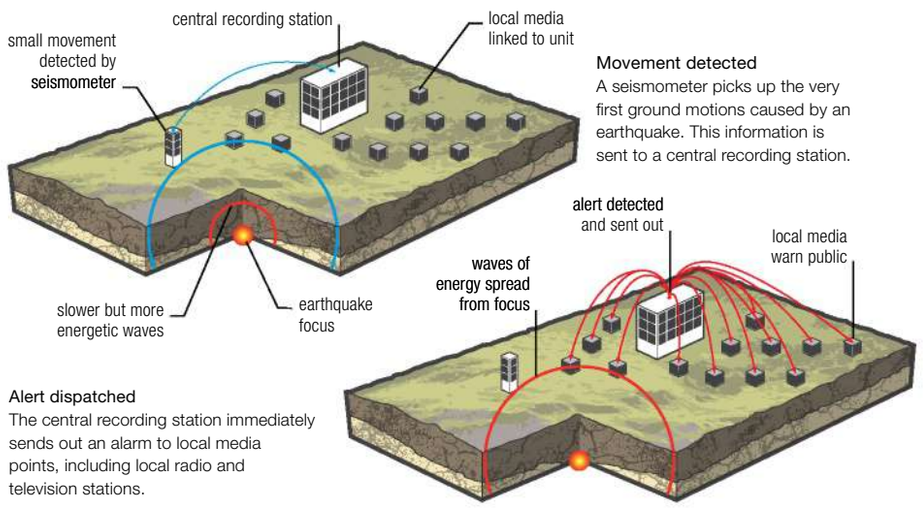
SAN FRANCISCO EARTHQUAKE RISK

This satellite image of California, USA, shows earthquake faults (red lines) and the San Andreas Fault (yellow line). The bands of colour are synthetic aperture radar patterns, which indicate seismic deformations resulting from a model earthquake on the San Andreas Fault. The model has estimated that there is a 25 per cent chance of an earthquake measuring magnitude-7 or above in the next 20 years on the San Andreas Fault.



JAPAN'S EARLY EARTHQUAKE WARNING SYSTEM

The Japanese Meteorological Agency has placed a network of sensitive instruments throughout Japan, designed to pick up the characteristic ground motions that occur in the first few seconds of a large earthquake. These motions trigger the Earthquake Early Warning System, linked to civil defence organizations and television and radio stations, which can then broadcast a coordinated plan of action.



Movement detected
A seismometer picks up the very first ground motions caused by an earthquake. This information is sent to a central recording station.

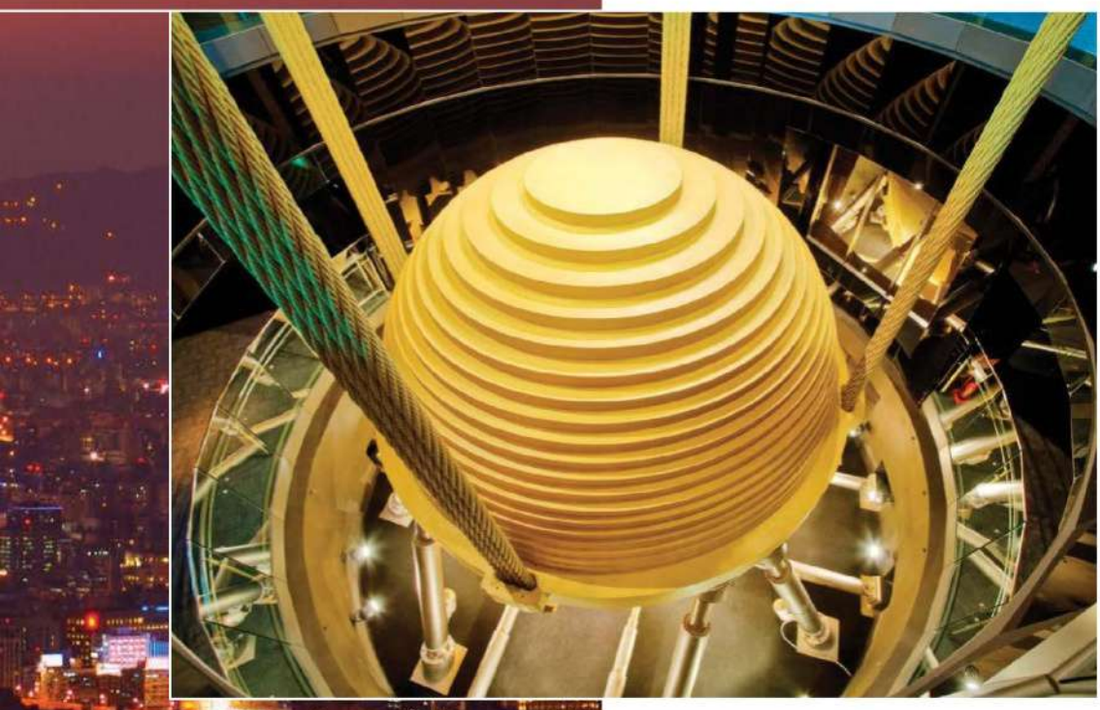
Alert dispatched
The central recording station immediately sends out an alarm to local media points, including local radio and television stations.



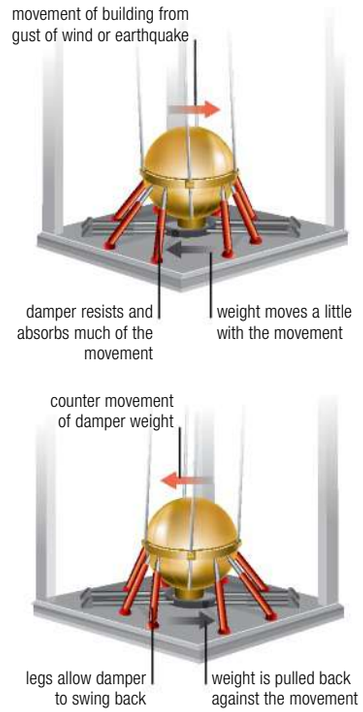
TAIPEI 101
One of the world's tallest buildings at 509m (1670ft), the Taipai 101 relies on its mass dampers to counter high winds or earthquakes.

EARTHQUAKE-PROOF BUILDINGS

In reality there is no such thing as an earthquake-proof building, though simple strengthening will greatly reduce the damage from a moderate earthquake. Engineers have studied the effect of the complex ground movements during a big earthquake on buildings, bridges, and other major structures, in order to find ways to reduce the risk of collapse, or to allow the building to fall in such a way that the loss of life might be minimized by the provision of internal refuge pockets. One solution is to increase the strength of the internal structure and foundations, reinforcing them with steel or concrete bracing. The shaking of a building can also be reduced, either by isolating it with so-called base isolators, made of a soft metal such as lead, in the foundations, or by damping the vibration with heavy counterweights inside the building. Since the late 1960s, many countries have introduced design codes that specify the maximum ground movements a building should be able to withstand. These design codes have been updated over time, following studies of the effects of more recent earthquakes.



MASS DAMPER
A steel pendulum weighing 666 tonnes and costing $4 million acts as a mass damper. It is suspended from the 92nd to the 88th floor.



HOW THE MASS DAMPER WORKS
The mass damper is tuned to swing in a way that counteracts any swaying of the building caused by wind or earthquake shaking; in effect it acts as a gigantic shock absorber.

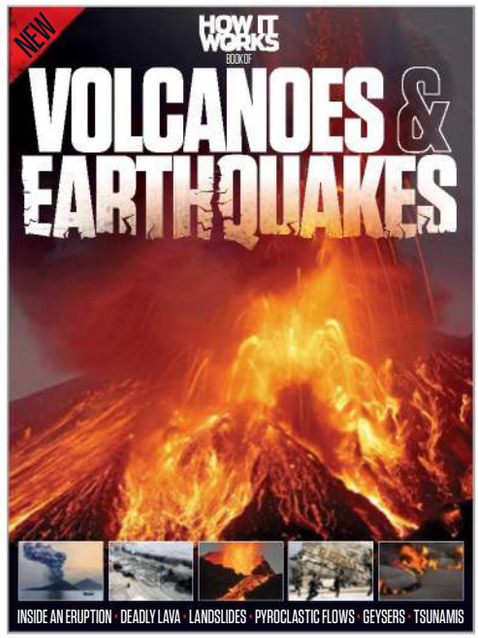
SEISMIC RETROFITTING

A large number of man-made structures in earthquake-prone regions were built when earthquake design codes were non-existent or less stringent. Removal of obviously weak parts such as towers, protruberances, or parapets make a building safer on the outside. Adding cross braces or new structural walls, or damping and isolation systems, will prevent internal collapse when a structure experiences the maximum ground accelerations specified in the design code. Experience in recent large earthquakes in California, New Zealand, Taiwan, and Japan, show that retrofitting is largely successful.



EARTHQUAKE REINFORCEMENT
This building in Berkeley, California, USA, near the Hayward Fault, has been encased in a cage of cross-braced steel struts to prevent it collapsing.

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